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8. AUTHORS
James Markham (PI), Patrick Bush, *Michael Best, *Alvin Berlin, and *William Lueckel

9. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Advanced Fuel Research, Inc.
87 Church Street
East Hartford, CT 06108-3728

***Advanced Power Systems International**
558 Lime Rock Road
Lakeville, CT 06039

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Naval Air Warfare Center – Aircraft Division
Highway 547 – Bldg 129, M/S 129-2
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13. ABSTRACT (Maximum 200 words)

Many of the naval bases proposed to accept deployment of the Joint Strike Fighter are in non-attainment of the National Ambient Air Quality Standard for the emissions of ozone precursors: oxides of nitrogen (NOx) and reactive volatile organic compounds (VOCs). The emissions of particulate matter including soot are also a concern. The Navy would benefit from a cleaner fuel so that high performance engines can run cleaner and criteria pollutants in the exhaust, regulated by the Clean Air Act, will be reduced. This project undertook demonstration of an innovative catalyst with potential to reformulate jet fuel to result in reduced emissions from gas turbine engines. Phase I work completed emissions measurements from a modular, atmospheric combustor, and a 3,300 lb thrust gas turbine engine. For both, jet fuel went through an exposure period to catalyst in the fuel storage tank before testing, and in-line canisters of catalyst were also tested. Emissions measurements were performed for sequential firing with untreated and treated fuels. Gas phase data from the atmospheric combustor (Jet-A and JP-8 fuels) and the turbine engine (Jet-A fuel) showed no measurable benefit in emissions reduction by any of the catalyst formulations tested. Smoke number data from the turbine engine also showed no measurable benefit, but the low smoke condition may have prevented conclusive observation.

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Emissions Reduction by Catalytic Reformulation of Jet Fuel

Preface

The work reported herein was conducted by Advanced Fuel Research, Inc. (AFR), 87 Church Street, East Hartford, CT 06108 and Advanced Power Systems International, Inc. (APSI), 558 Lime Rock Road, Lakeville, CT 06039 under U.S. Navy DOD Phase I contract number N68335-02-C-3080 with project monitoring by Naval Air Warfare Center – Aircraft Division, Code 4.8.1.4 – M/S Bldg 562, NAES Route 547, Lakehurst, NJ 08733. The NAVAIR Technical Liaison/Point of Contact was Ms. Gabrielle Korosec.

AFR and APSI express appreciation to the following individuals for guidance and interactions during the Phase I project:

Naval Air Warfare Center – Aircraft Division

Gabrielle Korosec

Rick Kamin

Chris Van Erp

Jack Buffin

Pratt & Whitney

Tedd Biddle

Curtis Genay

John Blondin

Chu Vu

Paul Hunt

Bill Atkinson

Arnold Air Force Base (AEDC)

Paul Jalbert

Vince Zaccardi

Don Gardner

Middle Tennessee State Univ.

Bill Allen

UTRC

Med Colket

AFR and APSI also appreciates the many others at P&W, AEDC and MTSU who contributed time and effort to arranging and/or aiding in the field tests.

Executive Summary

This project undertook demonstration of an innovative catalyst with potential to reformulate jet fuel to result in reduced emissions from gas turbine engines. Several variations of catalysts were tested for effect on Jet-A and JP-8 fuels, with firing in both an atmospheric pressure modular combustor rig (at Pratt & Whitney in East Hartford, CT) and a Pratt and Whitney JT-12 turbine engine (at the Middle Tennessee State University Airfield in Murfreesboro, TN). For both tests the jet fuels were exposed to catalyst well before testing to provide good potential for reformulation to occur. This exposure time for the P&W and MTSU field tests were >90 hours and >168 hours, respectively. In-line treatment during the rig or engine firing was also added for several test cases.

During testing at P&W, the gas phase emissions from the modular combustor rig were measured at two different rig operating conditions to show the effects of the catalysts on jet fuel. Measurements were collected when the rig was running at the optimum efficiency and with the rig running below optimum efficiency. For both cases, data acquired showed no measurable reduction in emissions for fuel exposed to catalyst compared to standard fuel.

Emissions monitoring (gas phase and particulate phase) at MTSU was performed over several power settings of the JT-12 turbine engine, ranging from 40% to 80% power. Emission levels were observed to change with the engine power settings, but showed no measurable reduction in emissions for fuel exposed to catalyst compared to standard fuel.

Mil-spec testing for several fuel parameters specified in MIL-DIL-5624T indicated that exposure of JP-8 fuel to two of the catalyst formulations used in this study did not result in deviation from acceptable values for standard JP-8.

Navy Phase I SBIR Final Report

"Emissions Reduction by Catalytic Reformulation of Jet Fuel"

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Detail Report

a. The Problem

The United States military relies on the combustion of hydrocarbon based jet fuel. Between 4 and 5 billion gallons are consumed per year, with exhaust emissions introduced into the global environment. A concern to the mission readiness of the Navy is that many bases proposed to accept deployment of the Joint Strike Fighter (JSF) are in non-attainment of the National Ambient Air Quality Standard (NAAQS) for the emissions of ozone precursors: oxides of nitrogen (NO_x) and reactive volatile organic compounds (VOCs). The emissions of particulate matter, including soot, are also a concern since a number of the naval bases are in areas that are classified as in non-attainment for PM10 (particulate matter of 10 microns or less). Particulate emissions and soot also lead to increased engine and fuel system components maintenance cost, decreased engine life, and decreased aircraft/engine availability. The Navy would benefit from a cleaner fuel so that high performance engines can run cleaner and criteria pollutants in the exhaust, regulated by the Clean Air Act, will be reduced. Such a fuel would also benefit other branches of the military, the commercial aircraft sector, and the global environment.

b. The Opportunity for Solution

The Phase I project was put in place with the potential to demonstrate the feasibility of a novel, innovative fuel catalyst that would significantly lower the pollution emissions from engines fired with jet fuel. The innovation was focused on a catalyst to be placed in the fuel storage tank or in the fuel supply line.

This project is a joint venture between Advanced Power Systems International, Inc. (APSI) and Advanced Fuel Research, Inc. (AFR). APSI hold key patents [1-4] protecting the underlying technology of the proposed fuel catalyst. This underlying technology resulted in a product launched in 1998 for mitigating pollution from small, gasoline and diesel fueled engines (automobiles, motorcycles, chainsaws, lawnmowers, etc.). Dropped into the fuel tank, significant decreases in exhaust pollutants have been well documented. Better engine performance and fuel efficiency have also been documented. Innovative chemistry and engineering based on this technology foundation will allow APSI to fabricate an optimized jet fuel treatment catalyst prototype for demonstrations on advanced turbine engines.

AFR brings expertise in new technology instrumentation for combustion monitoring and pollution emissions monitoring from turbine engines, including an advanced multigas analyzer that can simultaneously measure criteria pollutants and speciate unburned hydrocarbons on-site in real-time [5-9]. Funding for this work has been from DoD/Air Force, DoE, and EPA. Highlighted in DoD/BMDO [10] and DoE [11] fact sheets, development work of the multigas analyzer for propulsion turbine engine emissions monitoring has been done on location at engine test cells of Arnold Engineering Development Center (AEDC) of Arnold Air Force Base [6] and Pratt & Whitney [8-11].

In this 6 month Navy Phase I project, treated and untreated samples of Jet-A and modified Jet-A fuel (producing JP-8) were tested on a modular combustion rig (located at P&W in East Hartford, CT) to demonstrate the emissions reduction potential of several different catalyst formulations. Additional testing of both treated and untreated samples, with two different catalyst formulations, was done using a Pratt & Whitney JT-12 turbine engine (located at the Middle Tennessee State University, MTSU, in Mursfreeboro, TN). Finally, treated and untreated fuel was sent for laboratory testing to show that the catalyst does not degrade chemical and physical requirements for jet fuel.

Phase I consisted of 4 tasks and a 5th optional task with the following specific objectives:

Task 1 – Project Kick-Off Meeting, Prepare Catalyst, and Receive Jet Fuel Samples – The project kick-off meeting will allow the joint venture partners to review the project goals with the key groups at Pratt & Whitney, including the Emissions Group, the Instrumentation Group, the Combustion Systems Group, and the Fuels and Lubricants Group. The Phase I testing matrix will be reviewed and finalized. Two catalysts will be prepared for each fuel. One will be the standard FFC, and the other will substitute

zinc for the lead component and silver for the mercury component. Jet-A and JP-8 with the standard additives discussed in MIL-DTL-5624T will be used in the project.

Task 2 – Test Rig Combustion with Emissions Monitoring – This task will carry out the combustion rig testing at P&W. On-site emissions monitoring of the combustion exhaust stream from standard and reformulated fuels will confirm the reduction of contaminants afforded by the fuel catalyst. An additional field test measuring the emission exhaust from a P&W JT-12 turbine engine will confirm the effects of the catalyst has on fuel by reducing the emission gas concentrations from a typical turbine engine.

Task 3 – Mil-Spec Testing of Fuels – In this task, four of the ASTM standard test methods as specified in MIL-DTL-5624T will be performed to compare and evaluate treated fuel to untreated fuel. Completion of mil-spec testing requirements will be carried out in the Phase I Option Task.

Task 4 – Final Analysis, Presentation or Results and Phase II Planning – In this task, the test data of Task 2 and 3 will be analyzed. Results of fuel treated with catalyst will be compared to the un-treated fuel. Follow-up discussions and meeting with Pratt & Whitney will result in the Phase II plan. The analysis results of this task and the Phase II plan will also be presented to the Navy Project Monitor at a meeting in East Hartford, CT. The decision on proceeding to the Option Task (Task 5) and Phase II will be clear.

Task 5 (Option Task) – Completion of Mil Spec Testing and Phase II Test Plan – Tasks 1-4 will establish feasibility that will call for the Phase II project to proceed. This option task will be an excellent transition into Phase II. First, the final ASTM standard test methods specified in MIL-DTL-5624T will be completed. Second, discussions with Pratt & Whitney will finalize the matrix of additional rig testing and the progression to gas turbine engine testing in Phase II.

Task 1-4 were completed within the 6 month Phase I schedule. The option task was not implemented at the time of report submission.

c. Phase I Significant Results

The project kick-off meetings were held on the 14th of November 2001and 29th of November 2001 at Pratt & Whitney in East Hartford, CT and NAVAIR in Lakehurst, NJ, respectively. In attendance were the following:

14-Nov-01 at P&W
Jim Markham PI (Advanced Fuel Research – AFR)
Patrick Bush (AFR)
Mike Best (Advanced Power Systems International – APSI)
Al Berlin (APSI)
Tedd Biddle (Pratt & Whitney – P&W)
Curtis Genay (P&W)
Chu Vu (P&W)
John Blondin (P&W)
Paul Hunt (P&W)

29-Nov-01 at NAVAIR
Jim Markham PI (AFR)
Patrick Bush (AFR)
Mike Best (APSI)
Gabrielle Korosec (NAVAIR TPOC)
Rick Kamin (NAVAIR – phone)
Jean Hawkins (NAVAIR – phone)

The meeting at Lakehurst was arranged at the request of the NAVAIR TPOC, since a schedule conflict prohibited NAVAIR attendance at the Pratt & Whitney meeting. The contractors had planned to present project results at Lakehurst at the end of the project, but the TPOC suggested a NAVAIR visit to AFR near the end of the project for the presentation of results.

The PI provided the group, at both meetings, an overview of the project purpose, goals, and reviewed the planned schedule. Emphasis was placed on the testing matrix, which was finalized. The discussions focused on the testing matrix to one bulk fuel (Jet-A), which would be utilized as-received and with the military additives package blended in to produce JP-8. APSI received a small quantity of Jet-A fuel from P&W at the 14-Nov-01 meeting for laboratory testing. These tests provided APSI information for fabricating several catalyst formulations to be tested. Five catalyst formulations were fabricated to be

tested for emissions reduction on the as-received and blended fuel. The catalyst formulation identified as having the most significant reduction would be tested further to evaluate time of treatment effects to emissions reduction.

Emphasis was also placed on an extension pipe to be added to the Becon Burner testing at P&W, for exhaust gas cooling purposes. Finally, the PI introduced the plan for additional testing of the treated fuel on a Pratt & Whitney JT-12 turbine engine located at Middle Tennessee State University. The turbine engine test was offered to the project by the emissions measurement group at Arnold Engineering Development Center (AEDC) at Arnold Air Force Base, TN. The AEDC group is currently charged with JSF engine emissions testing at P&W in West Palm Beach, FL. The JT-12 engine test is an excellent opportunity for the Phase I project.

Field Test at Pratt & Whitney: Figure 1 is a photograph of the burner rig used at P&W for the first emissions reduction testing of jet fuel treated with catalyst. The burner rig is a modular combustor system previously developed by Pratt & Whitney and manufactured under license to Becon, Inc. The Becon laboratory combustor simulates the mixing, flow, and combustion chemistry of fuels in turbine engine combustors, but it is an atmospheric pressure combustor. It does not provide the high-pressure combustor conditions of a gas turbine engine. The picture in fig. 1 was taken during unrelated testing of a ceramic coated bar standing in the high temperature flame exiting the burner rig.

Figures 2-3 are photographs of the Becon Burner with the extension exhaust pipe attached. The extension pipe was built by AFR for this project to provide an enclosed flow path for the exhaust gas of the Becon burner to cool before sampling with the P&W multigas analyzer (MGA). The cooling extension pipe was designed and machined out of a stainless steel pipe (pipe size 5) approximately 10 feet in length. A 10 inch side port was welded on to the extension pipe, 7.75 inches from the burner outlet, to give a clear sight of the Becon burner flame during testing. Copper tubing was wrapped around the extension pipe covering approximately 5 feet, as well as the side port for water cooling. The extension pipe bolts onto the Becon burner with a high temperature gasket in place to prohibit ambient air from diluting the exhaust flow. With the extension pipe in place, the burner rig was fired with Jet-A fuel to bake out and condition the pipe in preparation for catalyst treated fuel testing. The extension pipe resulted in cooling of combustion gases down to approximately 1000°C. This temperature was acceptable for the stainless steel probe used to draw exhaust gas to the MGA. The 6ft long x ¼" stainless steel tube was connected to ~20ft of conventional heat trace gas sampling tubing set to 150°C. Sketch 1 presents a shematic of the sampling system to the MGA. Sample gas is delivered to the MGA at 150°C, at the same temperature of the measurement cell within the MGA [6,12].

AFR had 4 x 55gal. steel drums (closed head with 2" and ¾" bung openings on each) delivered to P&W. On 24 Jan 2002, P&W filled the drums with Jet-A fuel. AFR also provided P&W with a 16gpm air powered pump (McMaster-Carr part no. 8243K21) for mixing the appropriate additives into 2 of these drums of Jet-A fuel to produce JP-8 fuel. Mr. Jack Buffin at NAVAIR Patuxent River recommended this pump. Materials that come in contact with the fuel are type 316 stainless steel, Teflon, and Teflon-graphite composite.

On 25-26 Jan 2002, the four required additives were mixed into two of the drums of Jet-A to produce JP-8. The additives were Stadis 450 conductivity improver, fuel system icing inhibitor (FSII), DCI-4A lubricity improver, and AO-29 antioxidant. The mixing pump was set up to circulate the fuel in a drum by pumping out of the 2" bung hole and back into the ¾" bung hole. The mixing procedure was provided by P&W after telephone discussions with NAVAIR Patuxent River:

1. AO-29 is to be added first. Introduce the additive to the drum and circulate the fuel in the drum for an hour.
2. Stadis 450 conductivity improver is to be added second. Introduce the additive to the drum and circulate the fuel for an hour.
3. FSII is to be added third. Introduce the additive to the drum and circulate the fuel for an hour.

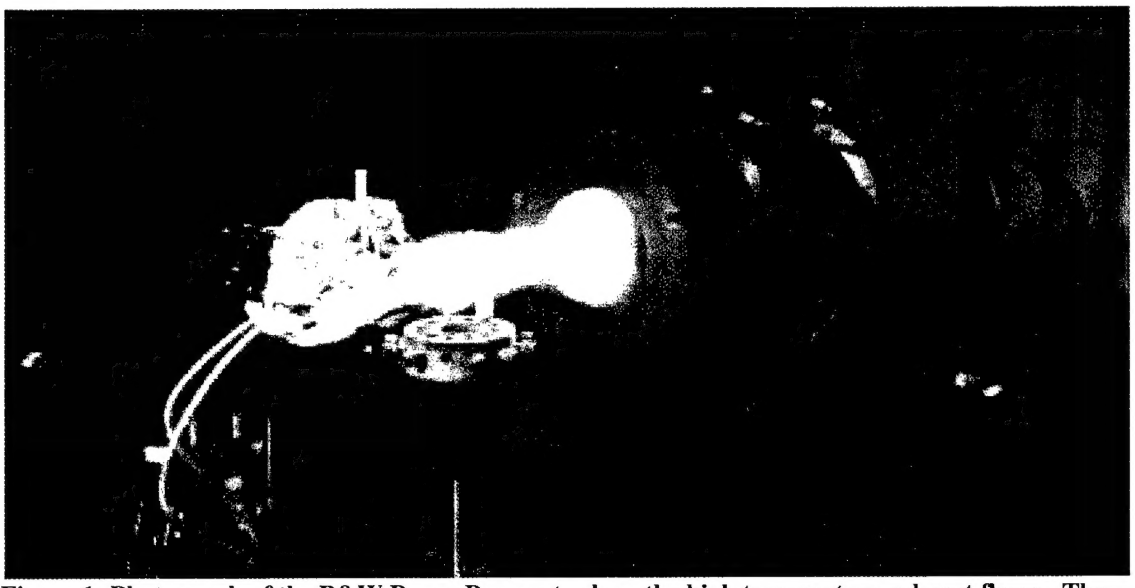


Figure 1: Photograph of the P&W Becon Burner to show the high temperature exhaust flame. The test article standing in the flame is unrelated to this project.

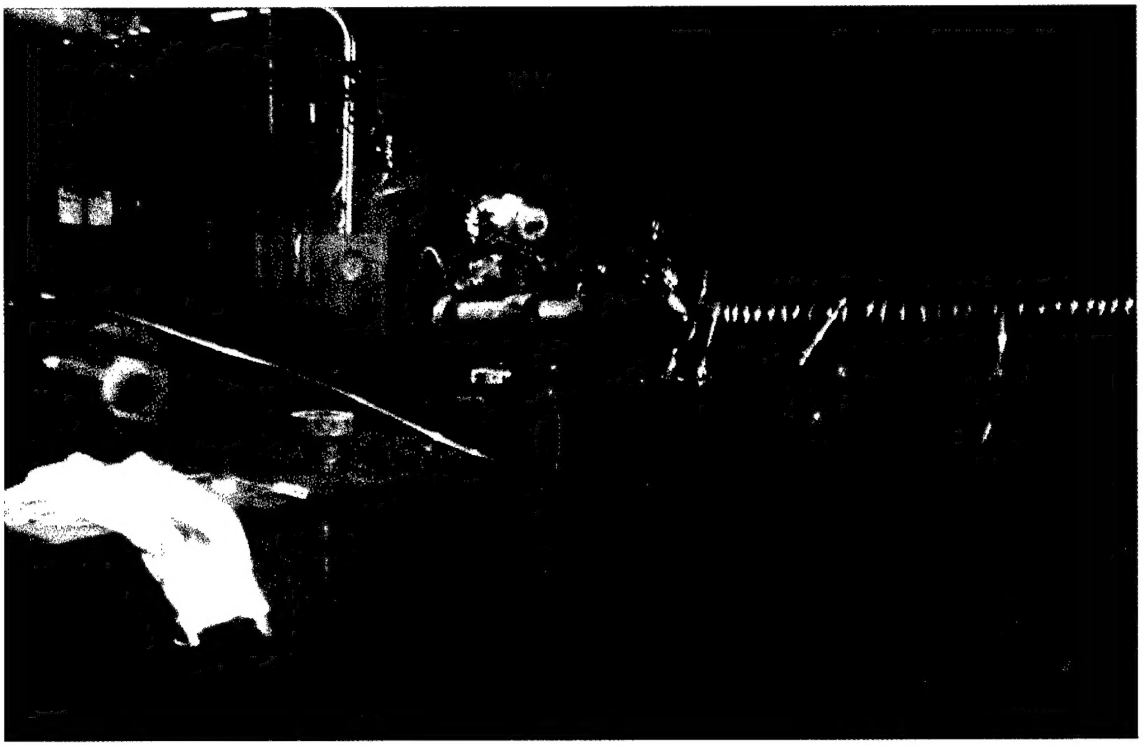


Figure 2: Burner rig with the 10' extension pipe attached.

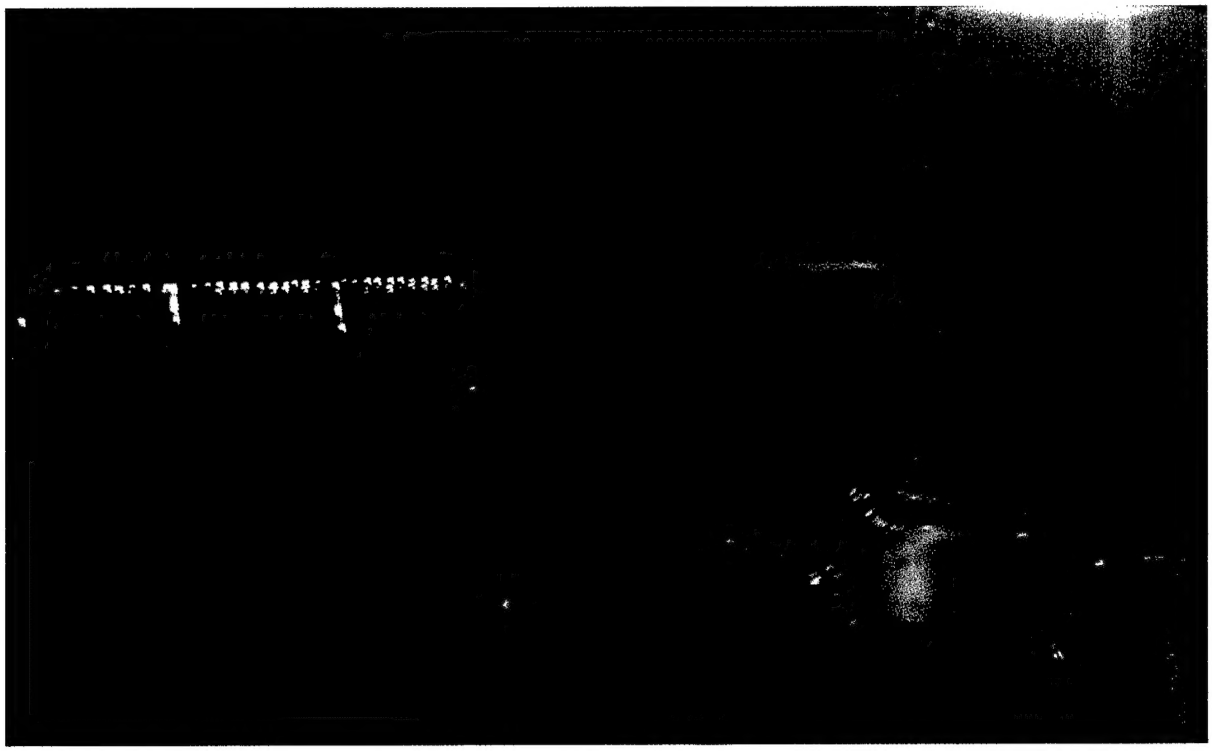
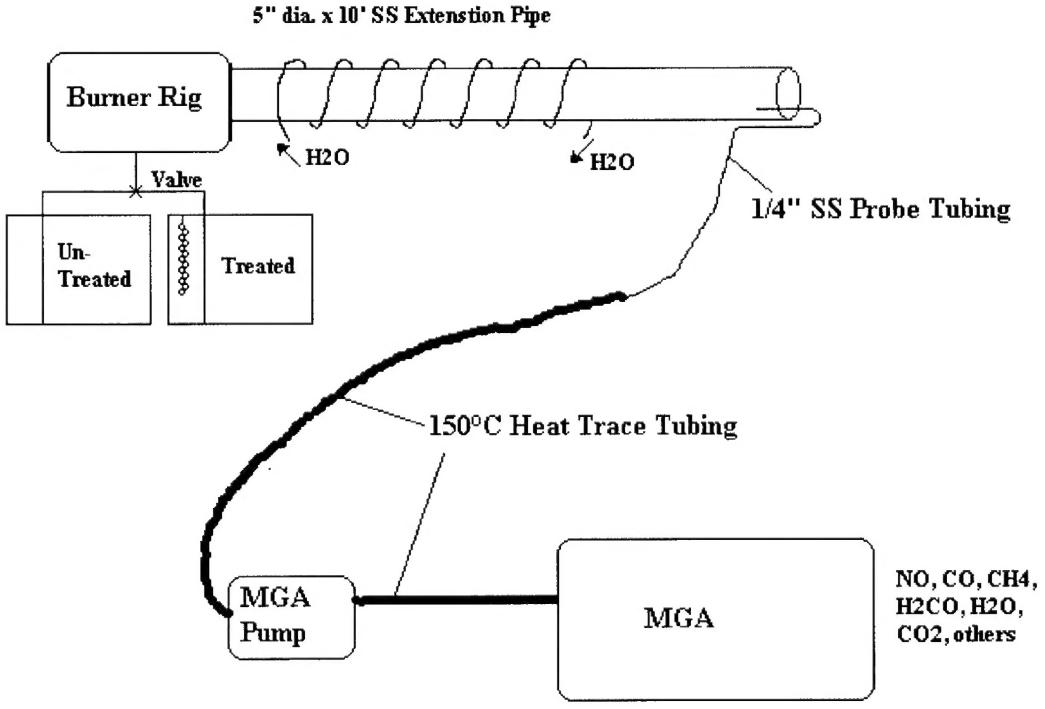


Figure 3: Exhaust end of the 10' extension pipe.



Sketch 1: Overview of the sampling for MGA analysts for P&W Becon Burner Testing.

4. DCI-4A is to be added lastly. Introduce the additive to the drum and circulate the fuel for an hour.

AFR received six different formulations of catalyst from APSI to "drop-in" fuel samples, and also two in-line canisters containing a catalyst. Since the plan was to split up the 55gal. drum samples into numerous 5gal. samples for catalyst treatment, APSI provided an amount of each "drop-in" catalyst appropriate for a 5gal. treatment. Five of the "drop-in" catalyst formulations were provided as ingots held in plastic, flow-through cage assemblies. Each cage assembly holds four ingots separated by a monel washer. Three of the five "drop-in" ingots were identified by the color of the plastic cage, and the other two were identified by the color as well as the absence of the monel washer. The sixth "drop-in" catalyst was provided in four 1" x 7" stock bars. The plastic cages and the hole dilled through the stock bars made it convenient to suspend each catalyst in the 5gal. containers with a nylon filament, as requested by APSI to increase surface contact of catalyst with fuel for this feasibility study.

Five gallon "GI Jerry Cans" (McMaster-Carr part no. 4303T5) were used for splitting and treating of Jet-A and JP-8 fuels. These are 20 gauge steel cans suitable for flammable liquids and designed to allow for fuel expansion. (They meet D.O.T-5B Title 49, NFPA 30, and are Massachusetts State Fire Marshal approved.) Table 1 indicates the fuel catalyst combinations prepared with the 5gal. Jerry cans.

The 5gal. cans were filled with fuel from the 55gal. drums on 25 Jan 2002. The cans containing catalyst were capped and shaken vigorously for ~30 seconds (requested by APSI). All samples were then stored inside at a P&W loading dock for ~90 hours before testing. Although inside, ambient temperature during storage at this location was cool, estimated by AFR in the range of 50-60°F.

On the day testing began, the 5gal. cans were transported the several hundred yards between the storage area and the Becon Burner building by loading them on a small flatbed transport vehicle. Typical agitation to the fuel samples occurred during loading, transport, and unloading.

Table 1: Five-gallon Samples for Atmospheric Burner Rig Testing at P&W

14 x 5gal. Samples	
Jet-A Fuel	**JP-8 Fuel**
Untreated (standard sample)	Untreated (standard sample)
Treated with black	Treated with black
Treated with red	Treated with red
Treated with yellow	Treated with yellow
Treated with stock bars	Treated with stock bars
Treated with red w/o monel	
Treated with yellow w/o monel	
Untreated (for use with in-line canister)	Untreated (for use with in-line canister)

To efficiently and selectively pull fuel from the 5gal. cans to feed the Becon Burner, a two-way valve was installed into the fuel line to allow the selection between two 5gal. cans in the delivery position (see sketch 1). A quick manual turn of the valve allowed the burner to run continuously without shutting down to change from one sample to another. This allowed the burner conditions to be set during initial start up with untreated fuel and to remain constant during testing. It also allowed us to conveniently alternate between untreated and treated fuel to determine if changes in the emissions profile over time were due to catalyst or slight drift in operational conditions during the time of testing.

Table 2 presents the matrix of fuel burns scheduled and performed in the Becon burner on 29 Jan. 2002. Presented in the table are the run times for each sample, the fuel-catalyst combination, and an incremental designation for reference to the data files collected with the multigas analyzer (MGA). Also indicated is the off vs. on position for a commercial product called the Fuel Smart™ Electronic Combustion Enhancer

Table 2: Matrix of Fuel-Catalyst Combustion During Becon Burner Testing

Time	Fuel	File Designation	Sample	Catalyst	Electronic Enhancer
0-5 min.	Jet-A	a1	untreated	n/a	off
5-10 min.	Jet-A	a2	untreated	n/a	on
10-15 min.	Jet-A	a3	treated	black	off
15-20 min.	Jet-A	a4	treated	black	on
20-25 min.	Jet-A	a5	untreated	n/a	off
25-30 min.	Jet-A	a6	treated	red	off
30-35 min.	Jet-A	a7	treated	red	on
35-40 min.	Jet-A	a8	untreated	n/a	off
40-45 min.	Jet-A	a9	treated	yellow	off
45-50 min.	Jet-A	a10	treated	yellow	on
50-55 min.	Jet-A	a11	untreated	n/a	off
55-60 min.	Jet-A	a12	treated	stock bars	off
60-65 min.	Jet-A	a13	treated	stock bars	on
65-70 min.	Jet-A	a14	untreated	n/a	off
70-75 min.	Jet-A	a15	treated	red w/o monel	off
75-80 min.	Jet-A	a16	treated	red w/o monel	on
80-85 min.	Jet-A	a17	untreated	n/a	off
85-90 min.	Jet-A	a18	treated	yellow w/o monel	off
90-95 min.	Jet-A	a19	treated	yellow w/o monel	on
100-105 min.	JP-8	jp1	untreated	n/a	off
105-110 min.	JP-8	jp2	untreated	n/a	on
110-115 min.	JP-8	jp3	treated	black	off
115-120 min.	JP-8	jp4	treated	black	on
120-125 min.	JP-8	jp5	untreated	n/a	off
125-130 min.	JP-8	jp6	treated	red	off
130-135 min.	JP-8	jp7	treated	red	on
135-140 min.	JP-8	jp8	untreated	n/a	off
140-145 min.	JP-8	jp9	treated	yellow	off
145-150 min.	JP-8	jp10	treated	yellow	on
150-155 min.	JP-8	jp11	untreated	n/a	off
155-160 min.	JP-8	jp12	treated	stock bars	off
160-165 min.	JP-8	jp13	treated	stock bars	on
0-5 min.	Jet-A	a21	treated	inline canister	off
5-10 min.	Jet-A	a22	treated	inline canister	on
10-15 min.	Jet-A	a23	treated	inline canister	off
15-20 min.	Jet-A	a24	untreated	n/a	off
25-30 min.	JP-8	jp21	treated	inline canister	off
30-35 min.	JP-8	jp22	treated	inline canister	on
35-40 min.	JP-8	jp23	treated	inline canister	off
40-45 min.	JP-8	jp24	treated	inline canister	on
45-50 min.	JP-8	jp25	untreated	n/a	off
50-55 min.	JP-8	jp26	treated	inline canister	off

provided by Energy Inc. Energy Inc. previously reported to APSI that their "electronic enhancer" has shown additional performance benefits when used with APSI catalyst applied to gasoline and diesel engines. The electronic enhancer provides an 8" coil that is wrapped around a metal fuel line. APSI requested that this unit also be tested within the catalyst matrix, and since it was not problematic to install, it was incorporated.

The entire series of drop in catalysts exposed to Jet-A were tested with the burner conditions of primary air set to 40 psi, secondary air set to 20 psi, and the fuel flow set at 100 psi. During operation of the burner, a thermocouple located near the outlet of the extension pipe allowed gas temperature to be recorded. Figure 4 presents a plot of NO and CO concentrations measured with the MGA as a function of time and sample. The gas concentration scale in parts per million (ppm) is on the left of the plot, and the gas temperature scale in degrees Celsius (°C) is on the right. The vertical lines in the plot distinguish the alternating continuous sequence between untreated and catalyst treated Jet-A fuel. A key to identify the label for each catalyst is provided above the plot in the Figure. For each time segment with catalyst, the electronic enhancer was "off" during the first half of each segment and "on" during the last half of each segment. Note that the time axis does not exactly match the time indicated in Table 2 since the 2-3 minutes of fuel sample transition time after switching from one sample to another is not included in fig. 4. The data traces in fig. 4 show no remarkable effects of any of the fuel catalysts or catalyst plus electronic enhancer on resulting NO and CO gas concentrations in the exhaust flow. At approximately the 35-minute mark on the plot, a 4-5°C temperature rise is observed. This was caused by a slight manual change in the burner input flow conditions. The P&W burner operator forgot to disengage an automatic shut-off timer on the burner, and in bringing the burner back on-line, the input flow conditions were slightly different. A sensitivity of the CO concentration is noticed (slight drop) with this small temperature increase.

Figures 5 and 6 are the similar plots for CO_2/H_2O and CH_4/formaldehyde concentrations respectively. Again, nothing remarkable is observed comparing untreated to treated fuel. The scatter in the H_2O data points is pointed out as not expected but may be instrument related. It is consistent throughout this series. CH_4 and formaldehyde are very low in concentration (less than 1 ppm) indicating efficient hydrocarbon consumption at this burner condition.

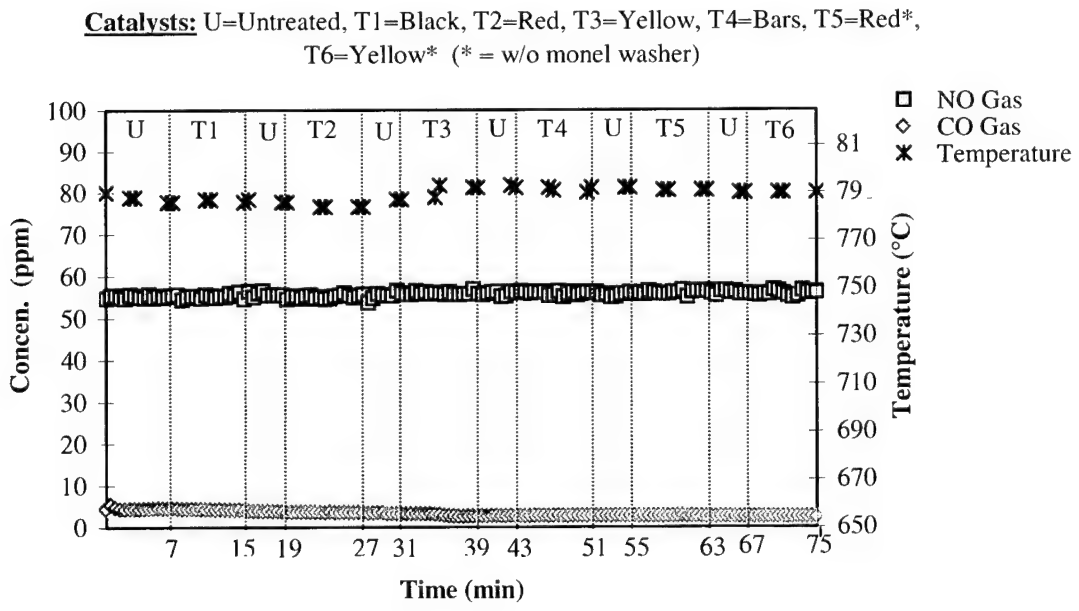


Figure 4: Concentration of NO & CO Gases (ppm) for "drop-in" Catalysts on Jet-A Fuel.

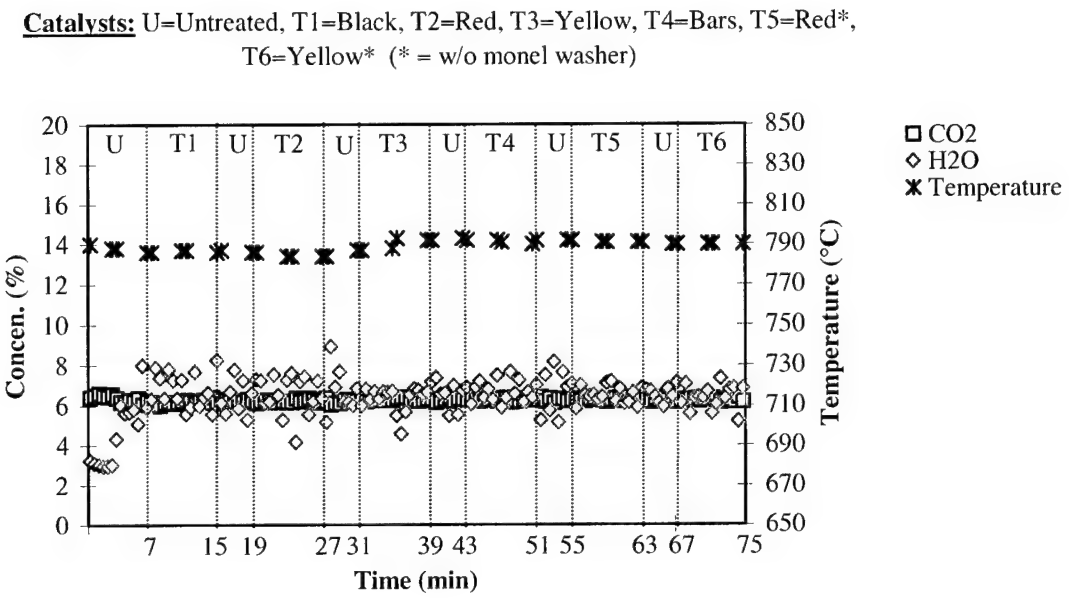


Figure 5: Concentration of H_2O & CO_2 Gases (%) for "drop-in" Catalysts on Jet-A Fuel.

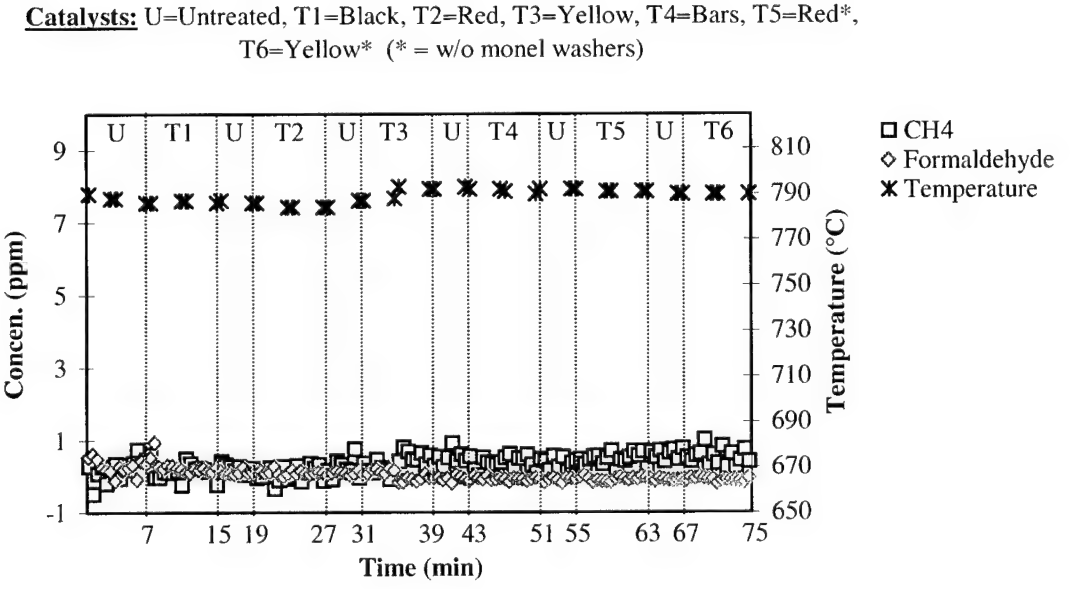


Figure 6: Concentration of CH_4 & Formaldehyde Gases (ppm) for "drop-in" Catalysts on Jet-A Fuel.

For the JP-8 fuel series, the burner conditions were adjusted so that higher CO emissions would be present and possibly provide a burner condition that would potentially be more influenced by catalyst interaction with the fuel. Therefore the entire series of "drop-in" catalysts exposed to JP-8 were tested with the burner conditions of primary air set at 50 psi, secondary air set at 30 psi, and fuel flow set to 100 psi. As shown in Figures 7-9, there were no obvious distinctions between untreated and treated JP-8 fuel. A slight decrease in CO concentration is pointed out from untreated JP-8 to the stock bar catalyst, approximately a 2 ppm drop in concentration. However, it is not obvious that this drop is related to the catalyst since there is a slight trend for CO to drop over the course of this entire series and may be related to burner flow stability. The drop is not considered as significant related to catalyst performance at this point.

The inline canisters were installed in the fuel line for testing, and the burner conditions were changed again to force the burner to burn even less efficient. The fuel flow was decrease to 75 psi, which resulted in the CO concentration to increase above 600 ppm. The P&W burner operator considered the firing conditions as unstable, and this is observed in the CO trace in Figure 10. The concentration of CO is drifting down while exhaust temperature is slightly increasing (albeit difficult to see the temperature drift in the Figure). The transition from the fuel treated with the in-line canister to untreated fuel does not provide an indication of remarkable effect by the catalyst for CO or for the other gases plotted in Figures 11and 12.

For the JP-8 series with the in-line canister, the fuel flow was increased to 100 psi at the recommendation of the P&W burner operator. Figure 13 for NO and CO concentrations again indicated a settling period from the beginning of the trace for stable flow conditions to occur. The transitions from treated to untreated and back to treated fuel samples are again viewed as unremarkable at this time for all exhaust gases measured (Figures 13-15).

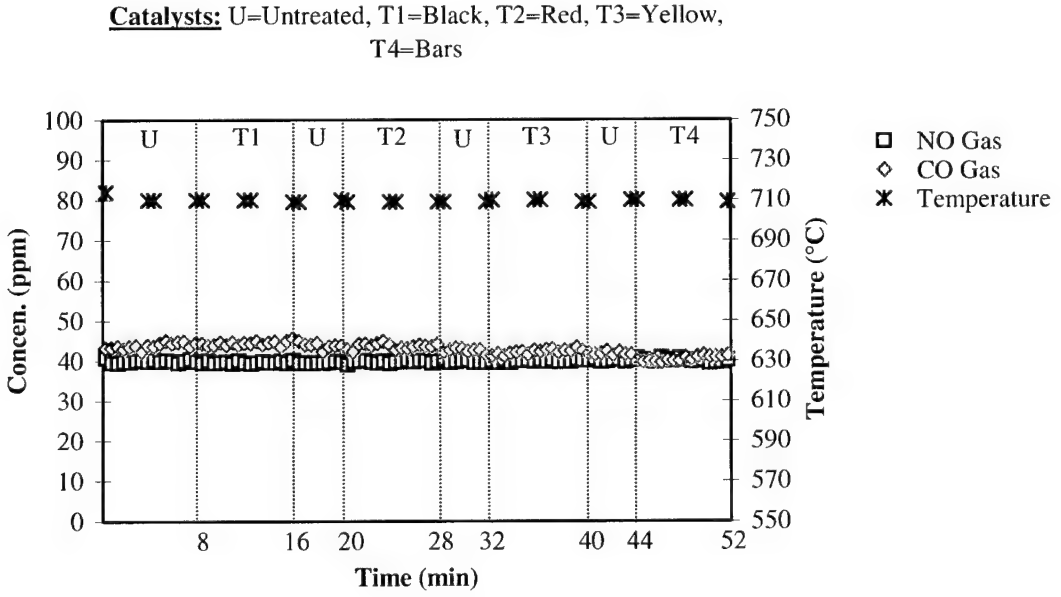


Figure 7: Concentration of NO & CO Gases (ppm) for "drop-in" Catalysts on JP-8 Fuel.

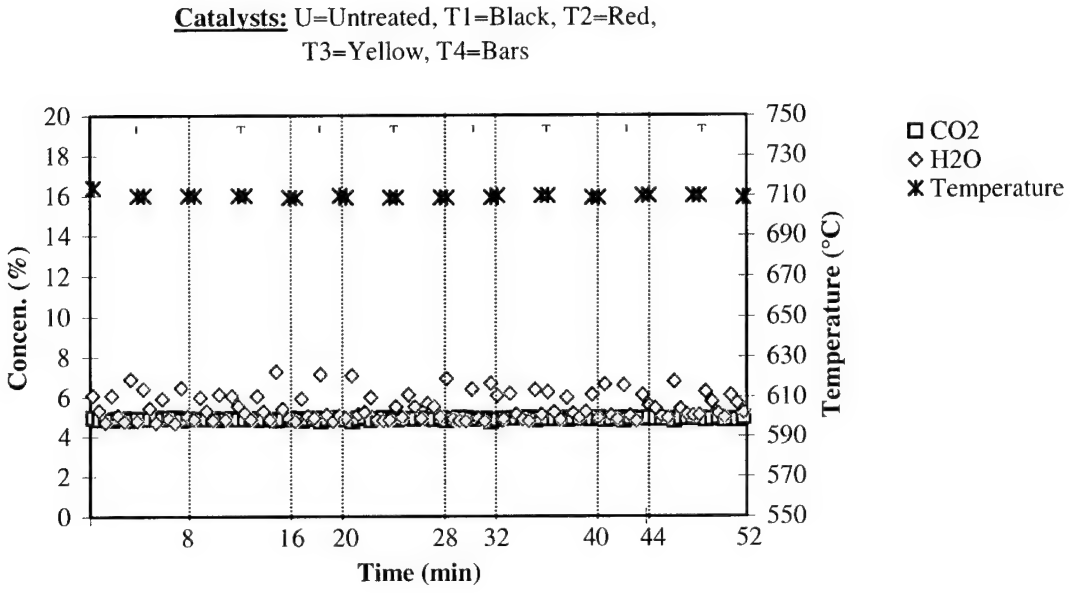


Figure 8: Concentration of H_2O & CO_2 Gases (%) for "drop-in" Catalysts on JP-8 Fuel.

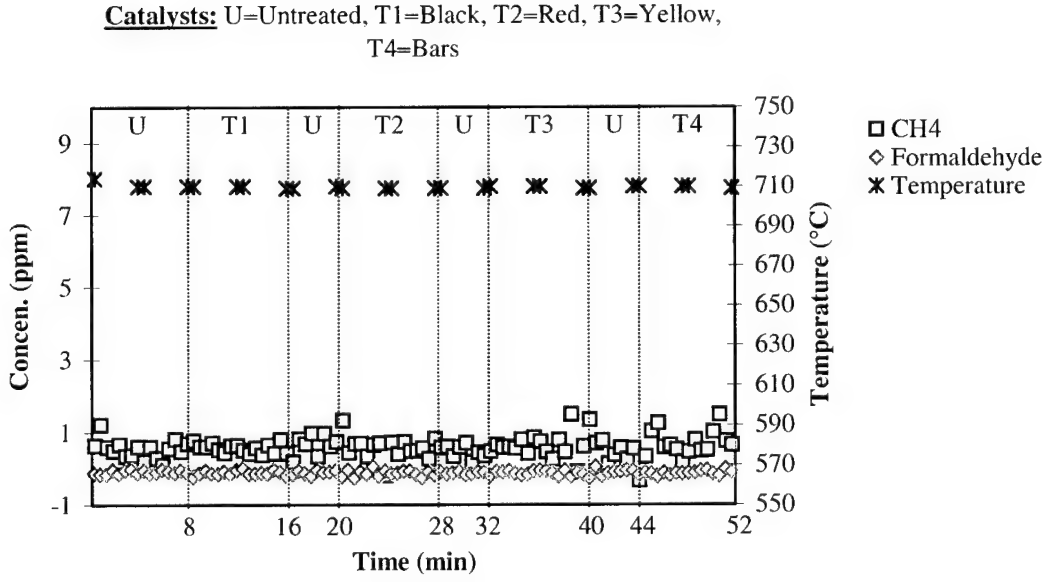


Figure 9: Concentration of CH_4 & Formaldehyde Gases (ppm) for "drop-in" Catalysts on JP-8 Fuel.

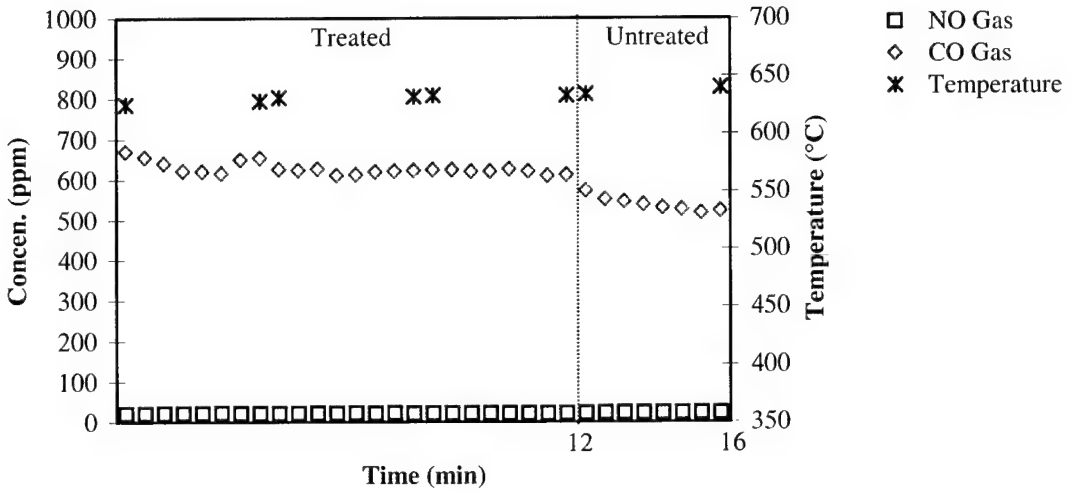


Figure 10: Concentration of NO & CO Gases (ppm) for "in-line" Canister on Jet-A Fuel.

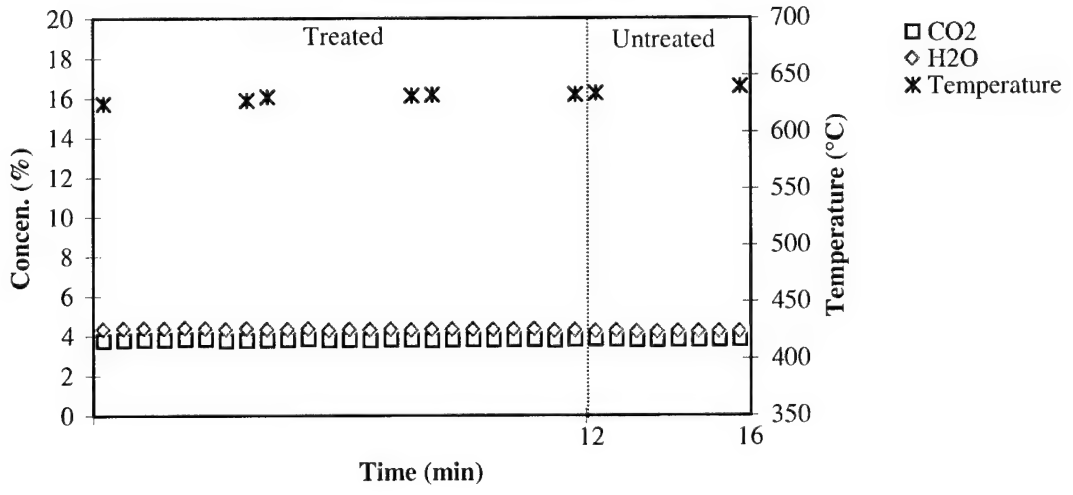


Figure 11: Concentration of H_2O & CO_2 Gases (%) for "in-line" Canister on Jet-A Fuel.

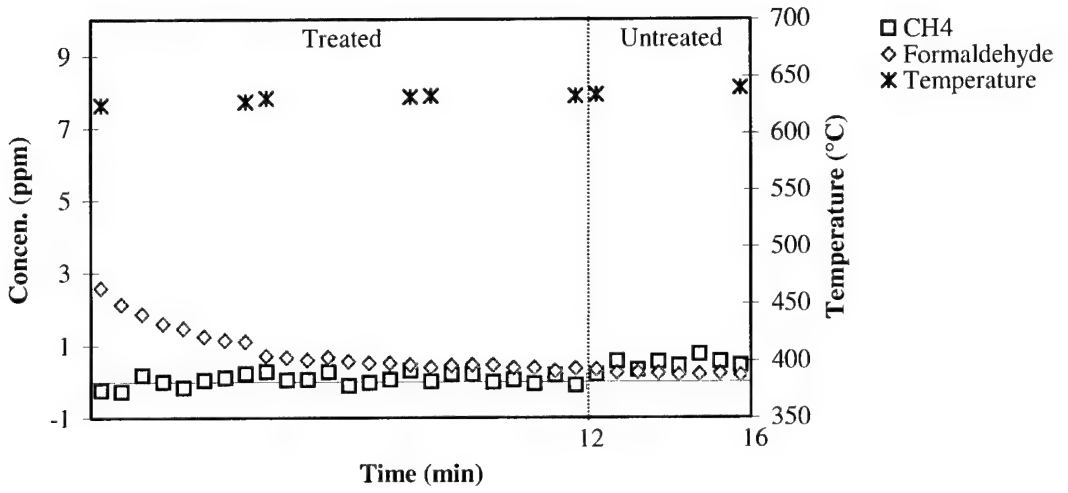


Figure 12: Concentration of CH_4 & Formaldehyde Gases (ppm) for "in-line" Canister on Jet-A Fuel.

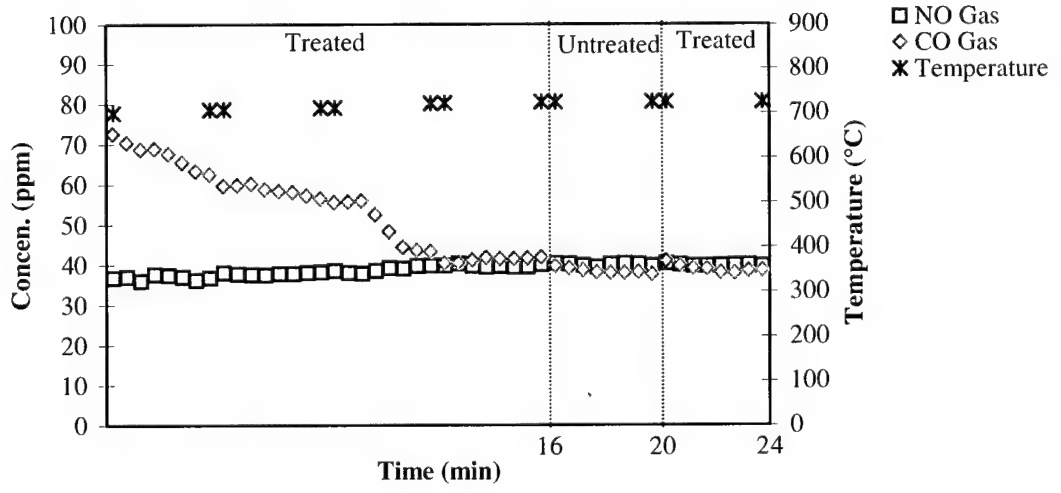


Figure 13: Concentration of NO & CO Gases (ppm) for "in-line" Canister on JP-8 Fuel.

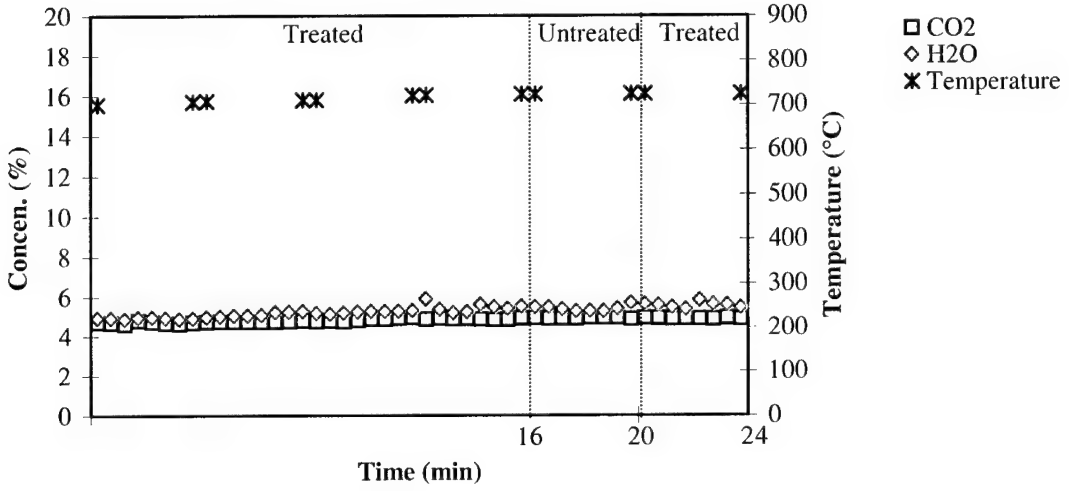


Figure 14: Concentration of H_2O & CO_2 Gases (%) for "in-line" Canister on JP-8 Fuel.

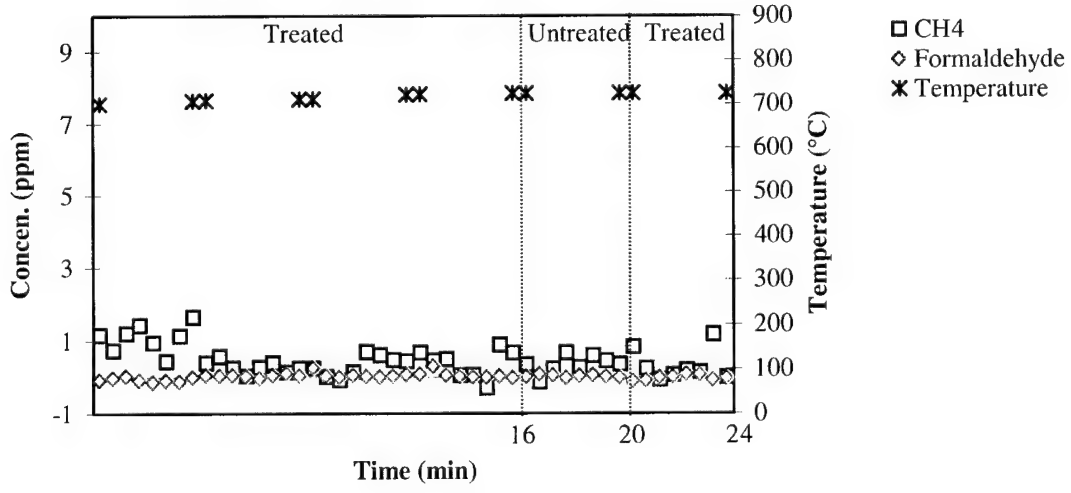


Figure 15: Concentration of CH_4 & Formaldehyde Gases (ppm) for "in-line" Canister on JP-8 Fuel.

Mil-Spec Testing: Two treated and one untreated sample of modified Jet-A fuel (JP-8) from the P&W field test in January were sent out to an independent laboratory (Saybolt, Inc.) for testing according to ASTM test methods that were specified in MIL-DTL-5624T, as well as, the ASTM method for testing the acidity of the sample. The ASTM methods are indicated in Table 3 along with the acceptable results for JP-8 fuel and the results of the three samples. The two treated samples of fuel were exposed to the catalysts for 33 days before the laboratory began testing. All three samples fell within the mil-spec for JP-8 fuel. Our interpretation of these results is that with the exception of particulate contaminants, the jet fuel showed no signs of degradation when exposed to the two catalysts. Particulate contaminants increased from 0.2mg/L (no catalyst) to 0.3mg/L (red catalyst) to 0.6mg/L (stock bar catalyst). However, it is pointed out that the stock bars were in their raw cast form (i.e. not polished and cleaned before contact with the fuel) and the red assemblies were not cleaned off of potential particulates picked up from its shipping container before contact with the fuel. These details were overlooked when the original fuel/catalyst combinations were prepared. Also, the treated samples of jet fuel could not be tested to show if the catalysts improved thermal stability, since Saybolt, Inc. was not willing to operate their test equipment in incrementally higher temperatures, than the standard 260°C, to identify the "break" temperature for each fuel sample.

Table 3: Mil-Spec test results of one untreated and two treated samples of JP-8.

				Results	
Test	**Method**	**JP-8 Standard for mil-spec**	**JP-8**	**JP-8 Red**	**JP-8 Stock Bars**
Gravity, API @ 60F	D-1298	37.0-51.0	44.0	44.0	44.0
Sulfur, X-Ray, Wt Pct	D-4294	0.4 (max)	0.0246	0.0240	0.0239
Gum, Unwashed, MG/100ML	D381	7.0 (max)	1	1	1
Heat of Combustion, BTU/LB	D-240		19824	19730	19824
BTU/GAL	D-240		133080	132447	133079
Net Heat of Combustion, BTU/LB	calc.	18400 (min)	18533	18439	18538
BTU/GAL	calc.		124412	123781	124447
Hydrogen, Wt Pct	D-5291	13.5 (min)	14.15	14.16	14.09
Particulate Contaminants, mg/L	D-5452	1.0 (max)	0.2	0.3	0.6
Acidity, total, MG KOH/GM	D-3242		0.021	0.023	0.020
Thermal Stability, JFTOT @ 260C	D-3241				
Pressure Drop, mm Hg		25 (max)	0	0	0
Tube Deposit Rating		<3 (max)	<1	<1	1

The reproducibility of the mil-spec results is not available since it is standard procedure for the independent laboratory to run each testing procedure once for each sample.

Field Test at MSTU: A schedule was put in place to test the fuel catalyst for emissions reduction with a P&W JT-12 gas turbine engine that is operated on an open test stand by Professor Bill Allen of the Aerospace Department at the Middle Tennessee State University (MTSU) in Murfreesboro, TN. This test schedule was arranged by the PI with benefit from the Instrumentation & Diagnostics Branch at Arnold Engineering Development Center (AEDC) of Arnold Air Force Base, TN, which is located ~40 miles from MTSU. The AEDC technical staff responsible for emissions measurements from military engines undergoing testing at AEDC offered to set-up their gas and smoke monitoring equipment at MTSU to support this test [12].

The JT-12 is a small, high performance single spool turbojet that can develop up to 3300 pounds of thrust, and is found mainly on small corporate jets such as the Lockheed Jetstar and Rockwell International's Buckeye and Saberliner models.

Four 55gal. drums were sent by AFR to Professor Allen, which he filled with Jet-A fuel. APSI supplied two catalyst formulations to treat two of the drums, plus two in-line vessels of type that is marketed for large displacement engines. Professor Allen placed the catalysts in the two drums on 8 March 2002. He then proceeded to build a valving system for convenient delivery of the fuel samples to his pump station and to the turbine engine. Figures 16-18 show pictures of the fuel handling system constructed. Figure 19 and 20 present pictures of the JT-12 engine with the AEDC emissions rake located in the exhaust flow path.

Measurements of treated and untreated Jet-A fuel were performed and completed on 15 Mar. 2002 for several power settings of a P&W JT-12 turbine engine. The Arnold Engineering Development Center (AEDC) emissions team had five instruments: 1) FT-IR multigas analyzer (same type of analyzer used at P&W on Becon rig test); 2) rack of single gas analyzers; 3) duplicate single gas NO_x analyzer; 4) filter paper based smoke meter; and 5) an optical based smoke meter. During each engine run, Professor Allen would bring the engine to a percent power setting as indicated in his control panel, and hold for several minutes for the condition to stabilize. Stability was determined by the CO reading of the MGA. Then up to several minutes of data would be collected before the signal was given to increase to the next power setting. Important to note is that the AEDC team installed a fuel flow meter to also monitor fuel consumption at each power setting. The engine runs were untreated Jet-A fuel, then Jet-A plus black catalyst, then Jet-A plus red catalyst, and then followed with a repeat of untreated Jet-A.

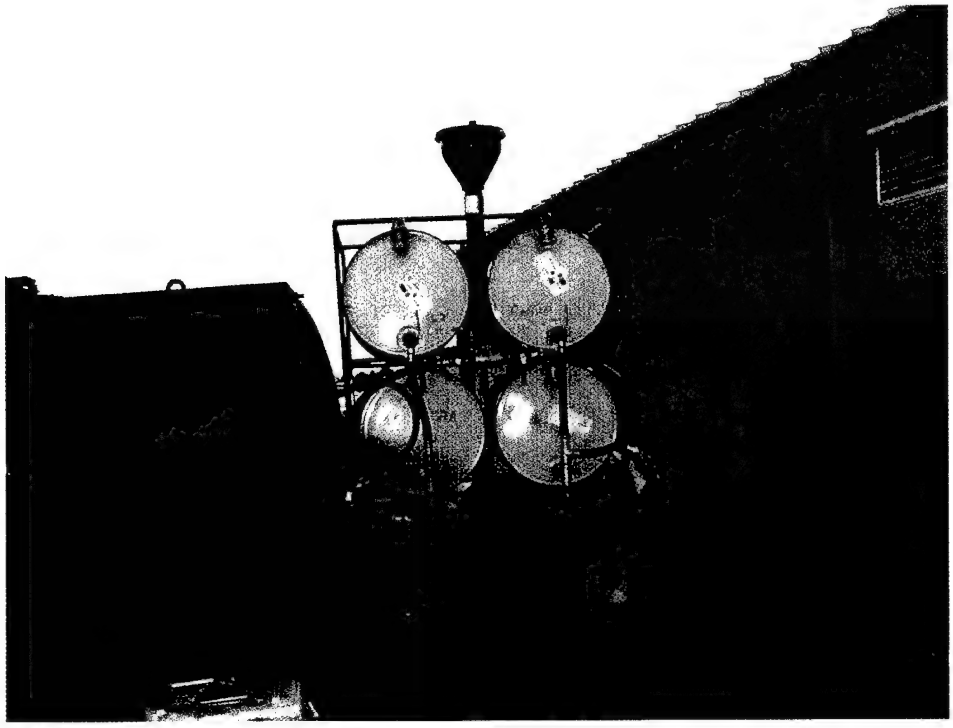


Figure 16: Four 55gal. drums containing untreated (bottom two) and treated (top two) Jet-A fuel.

Figure 17: Fitch Fuel vessel containing catalyst (F-10000).

Figure 18: Fitch Fuel vessels plumbed together in parallel.

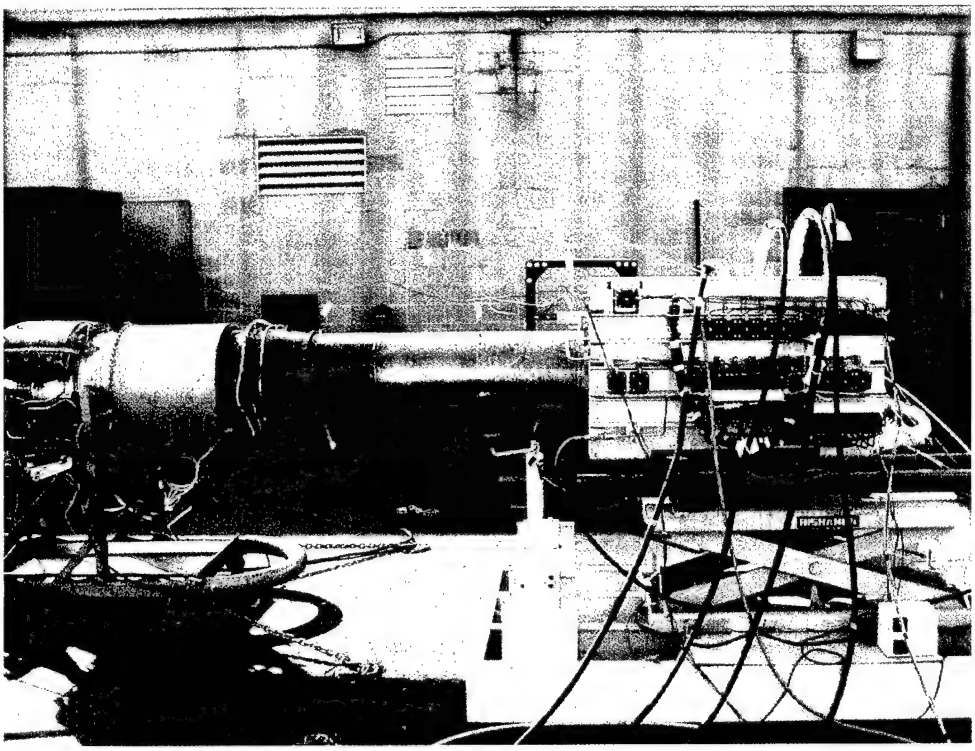


Figure 19: JT-12 turbine engine with the AEDC emissions rake in place.

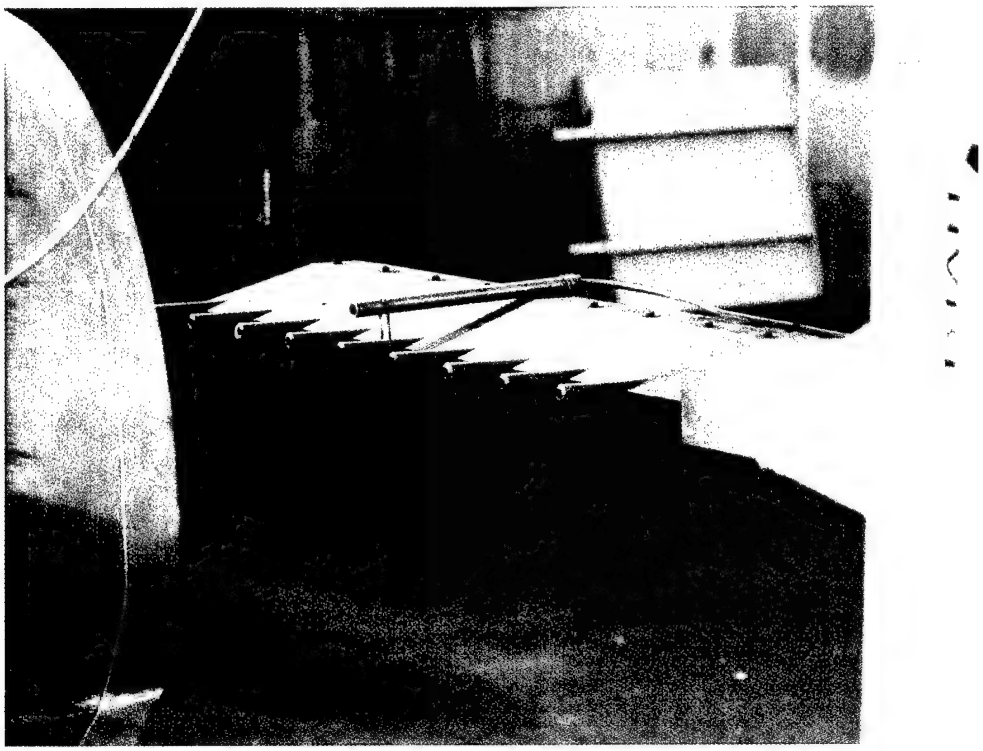


Figure 20: AEDC emissions rake in exhaust stream of the JT-12 engine.

Analysis of the data collected showed no remarkable signs of emission reduction caused by the catalysts. Figures 21-28 show the average gas concentrations (for NO_x, SO_2, CO, CO_2, H_2O, acetaldehyde, formaldehyde, and ethylene) of the untreated and treated samples of Jet-A fuel for the different engine power settings. Figure 29-36 present the concentrations as a function of the measured fuel flow rate. By either presentation, a benefit by the catalysts in gas emissions reduction is not indicated. There is also no indication of less fuel consumption as a result of the catalysts. Figure 37 plots the engine power settings vs. fuel flow rate, and no discernible pattern is observed. At higher engine settings the average NO_x concentration appears to come to a constant concentration of 14.75 and 14.0 for untreated and treated (red catalyst), respectively. Looking at the individual concentrations collected over the three-minute period (Figure 38) showed that the slight decrease in NO_x concentrations is within the measured deviations during the time period.

Figure 39 presents the smoke number (SN) measured with the optical smoke meter as a function of fuel flow rate. AEDC has experience in evaluating SN, and they concluded that the SN data suggested no measurable benefit from the catalysts. However, AEDC suggests that Jet-A may not be the best fuel to demonstrate a smoke number reduction with the catalysts since a SN less than five, measured on their optical smoke meter, may just as well be zero. With diesel firing, this size engine typically results in a SN in the 50-60 range.

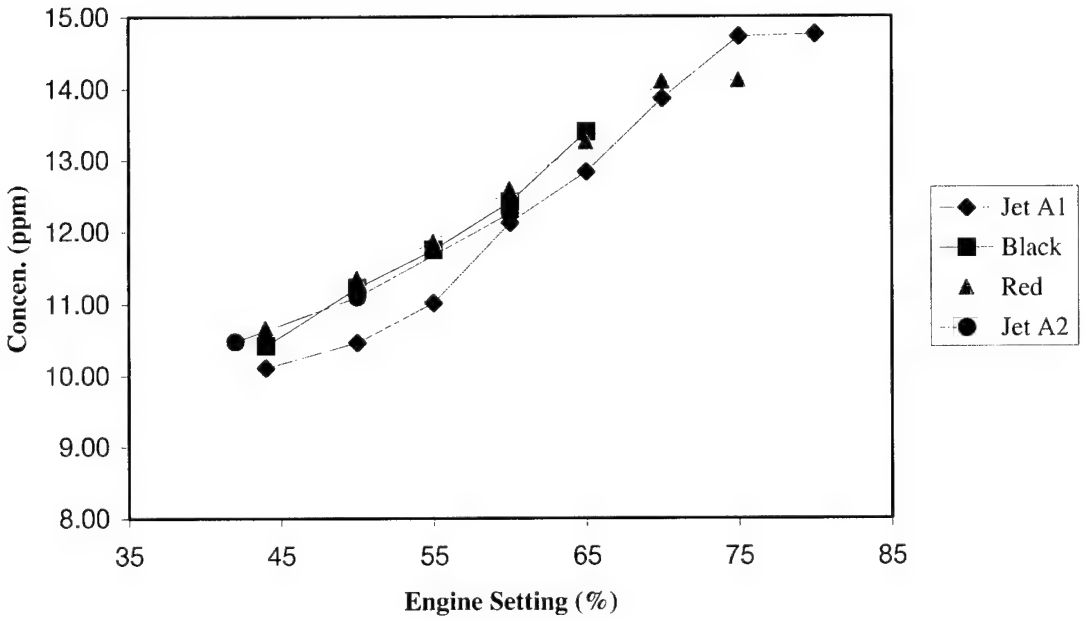


Figure 21: Concentration of NO_x vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

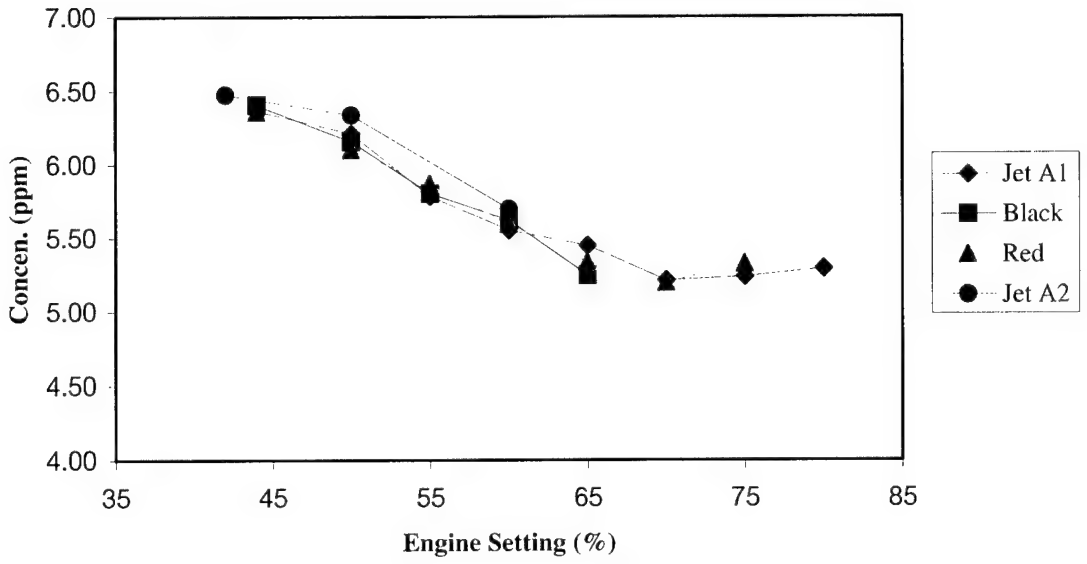


Figure 22: Concentration of SO_2 vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

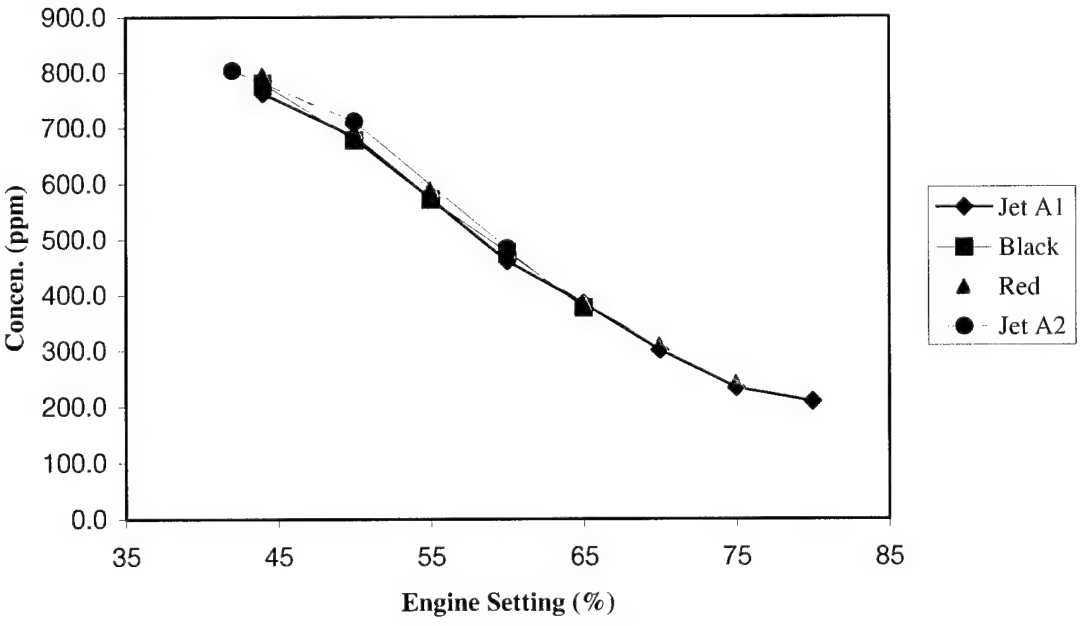


Figure 23: Concentration of CO vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

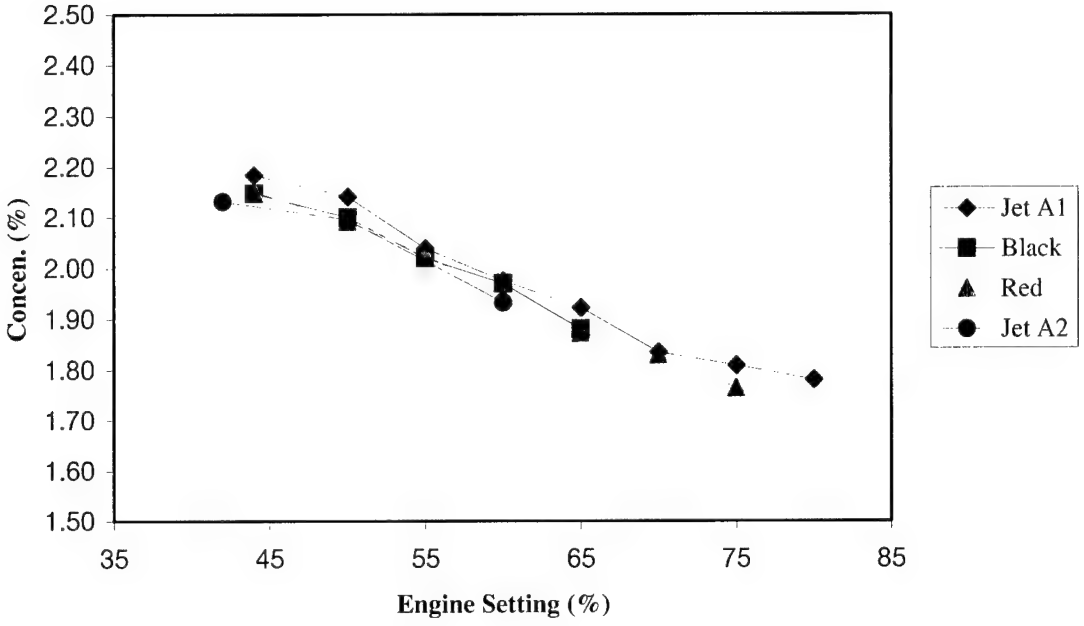


Figure 24: Concentration of CO_2 vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

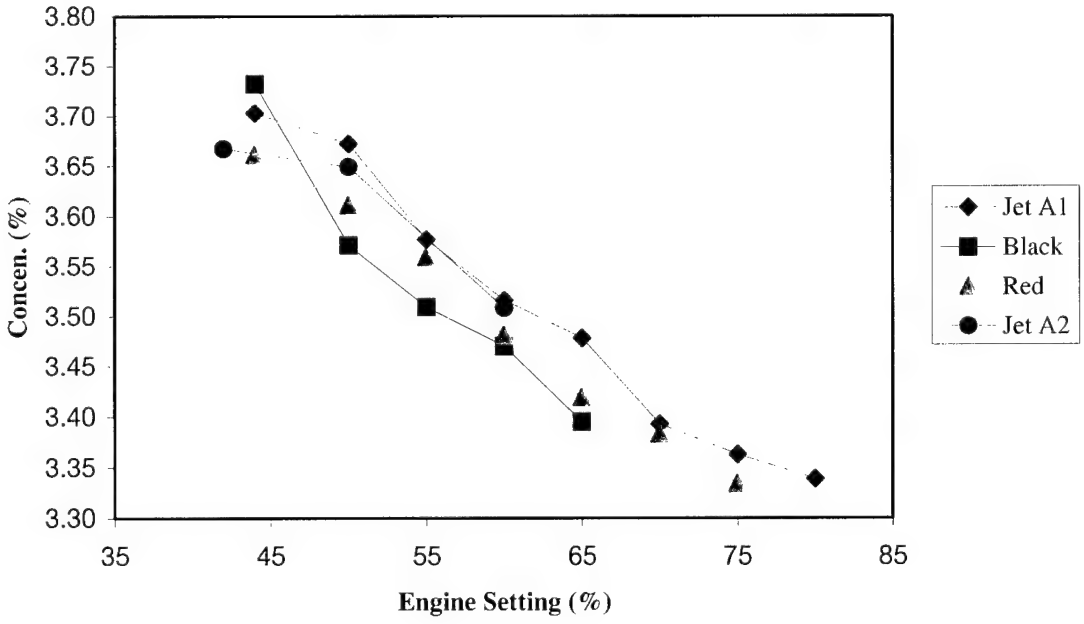


Figure 25: Concentration of H_2O Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

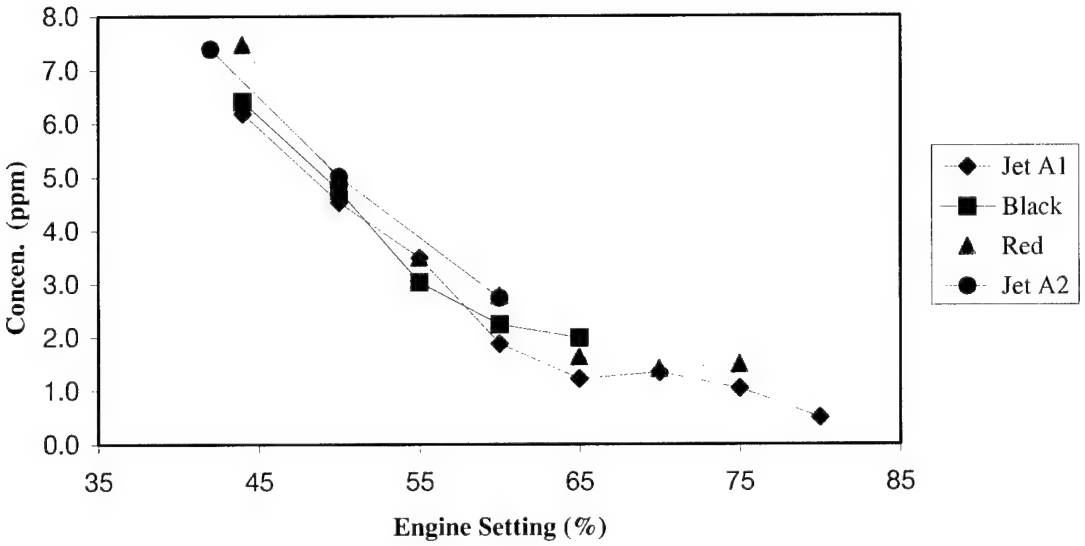


Figure 26: Concentration of Acetaldehyde vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

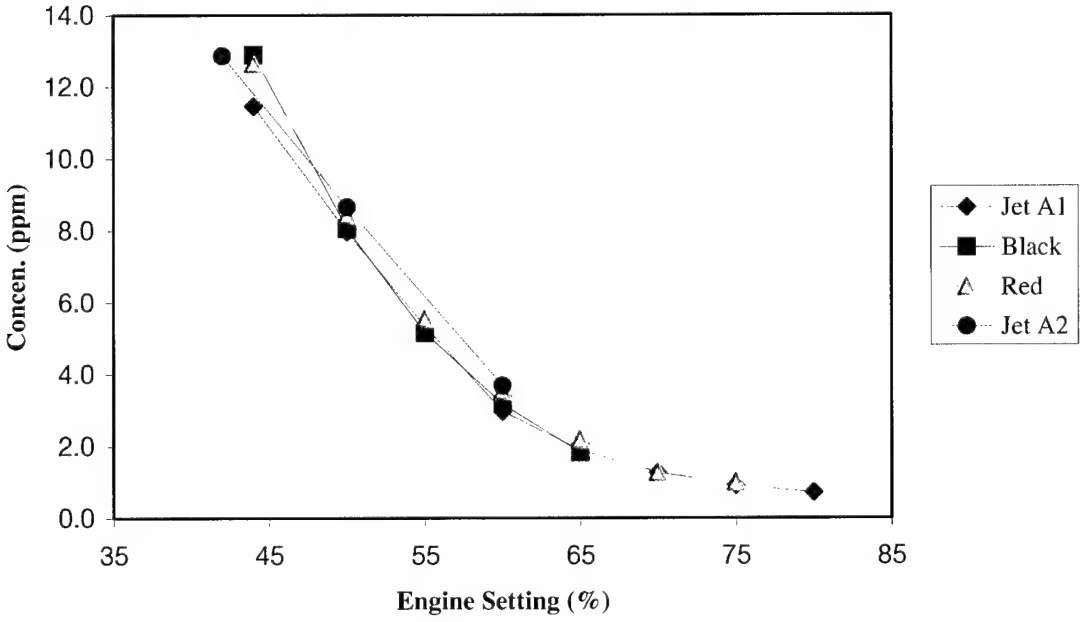


Figure 27: Concentration of Formaldehyde vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

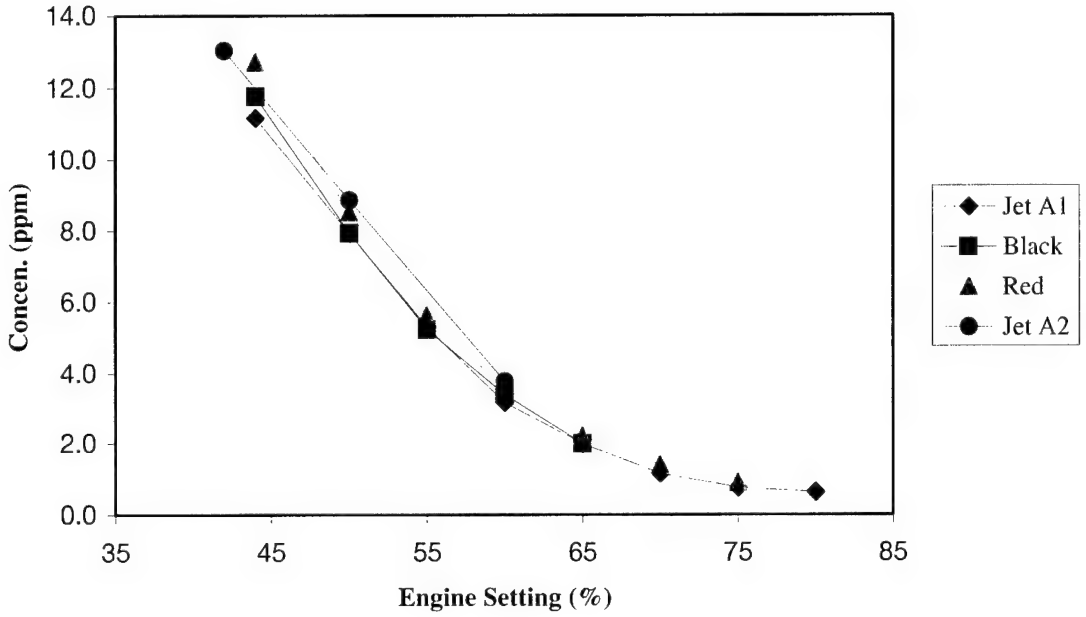


Figure 28: Concentration of Ethylene vs. Engine Setting for Treated Jet-A from JT-12 Turbine Engine.

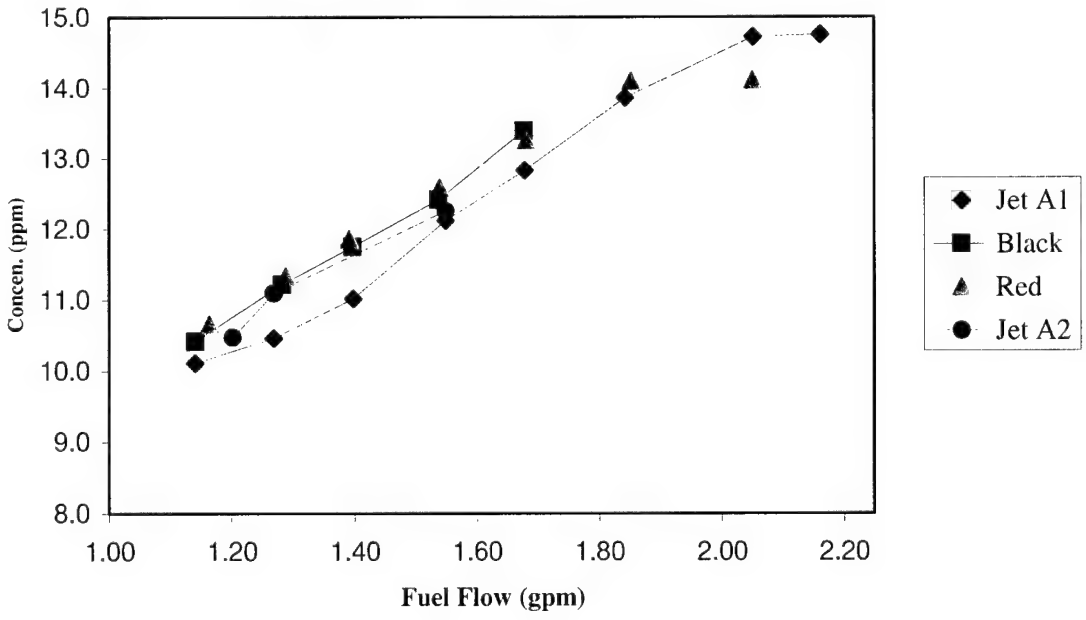


Figure 29: Concentration of NO_x vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

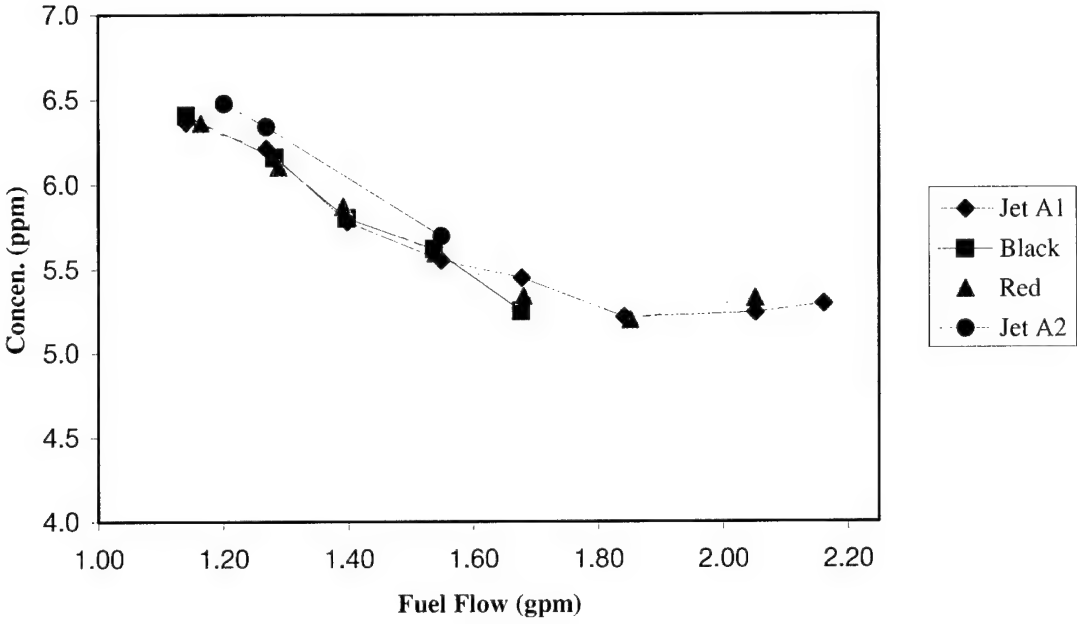


Figure 30: Concentration of SO_2 vs. Fuel Flow for Treated Jet-A from JT-12 Turbine Engine.

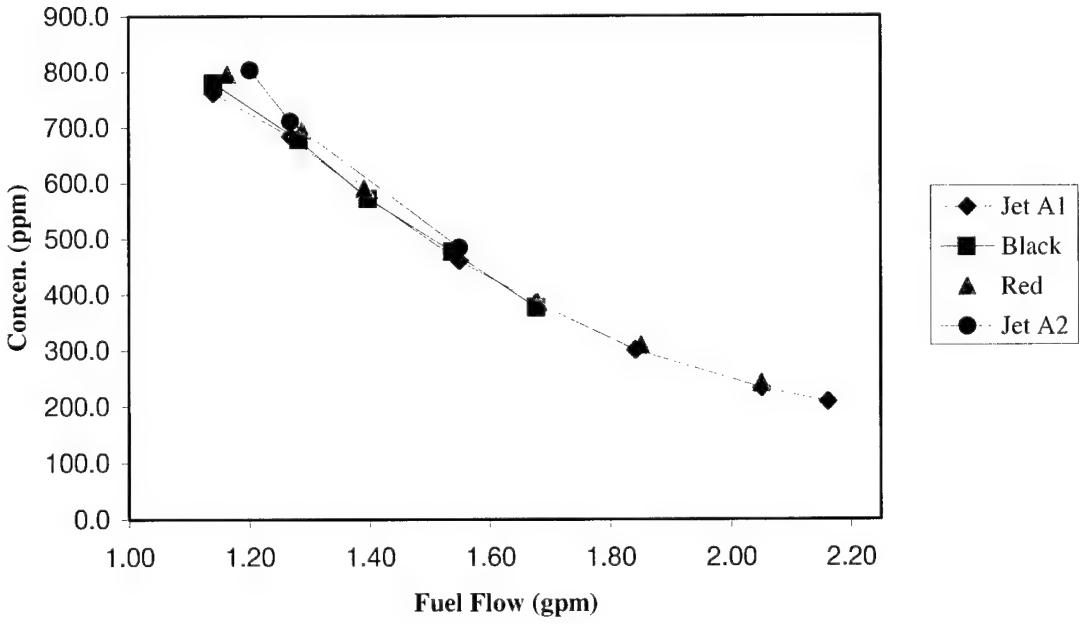


Figure 31: Concentration of CO vs. Fuel Flow for Treated Jet-A from JT-12 Turbine Engine.

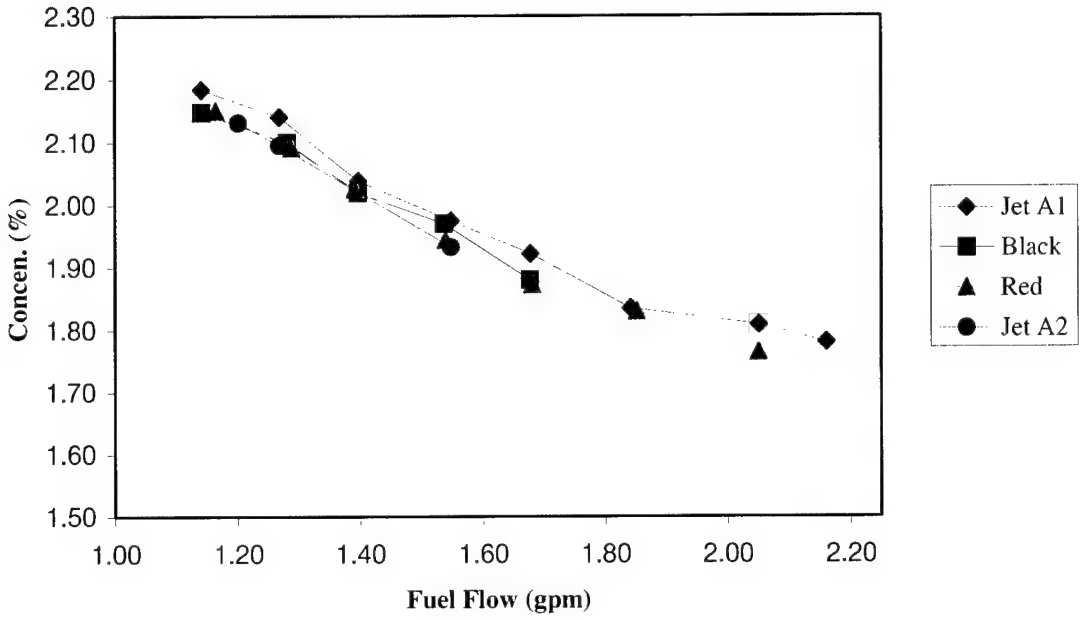


Figure 32: Concentration of CO_2 vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

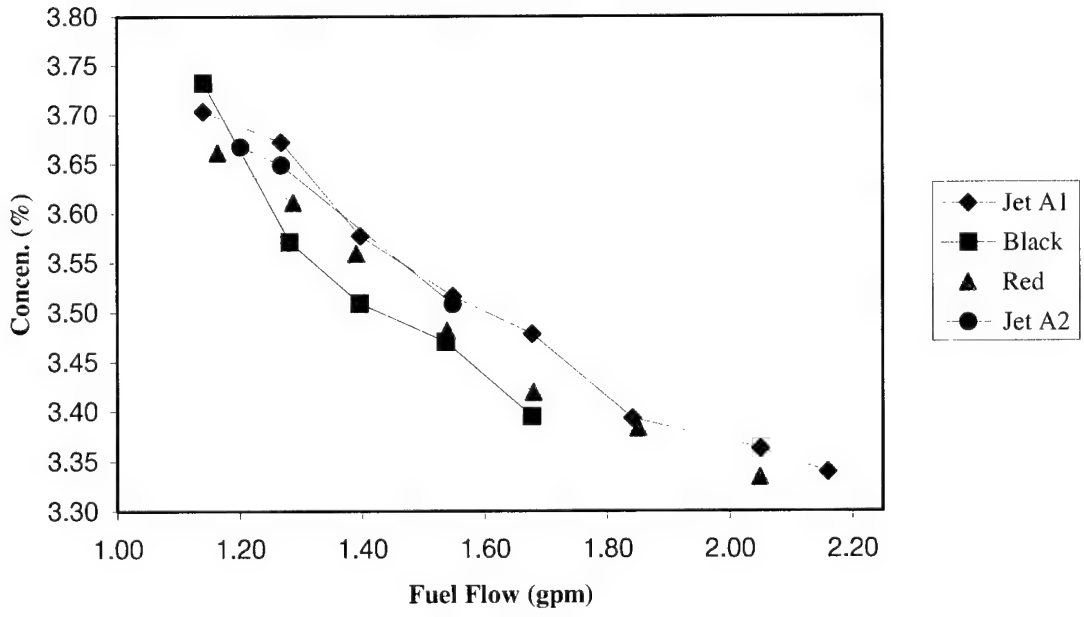


Figure 33: Concentration of H_2O vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

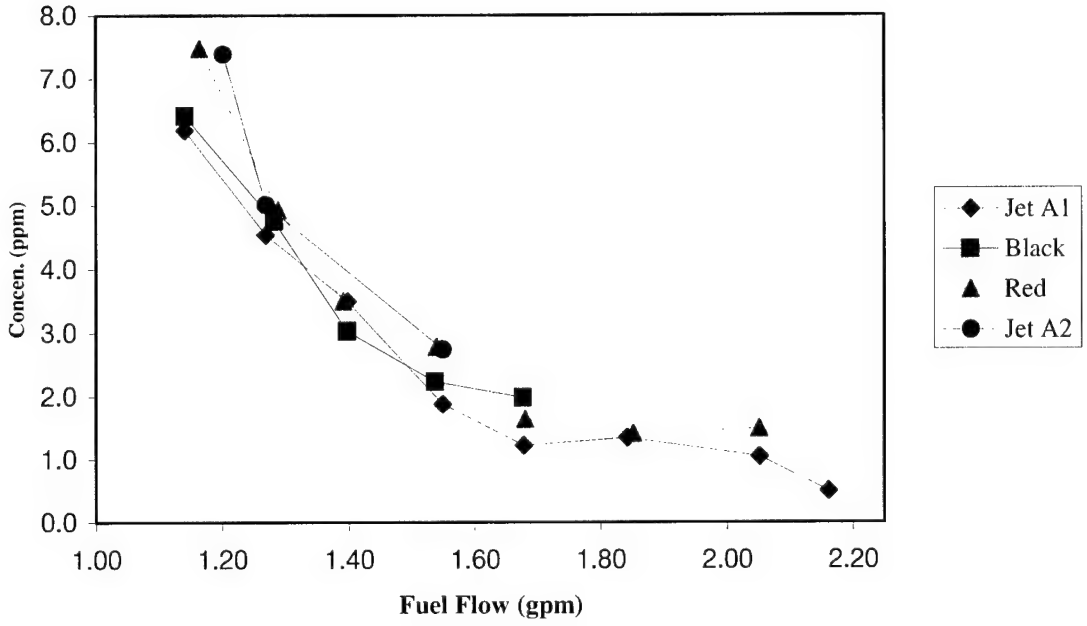


Figure 34: Concentration of Acetaldehyde vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

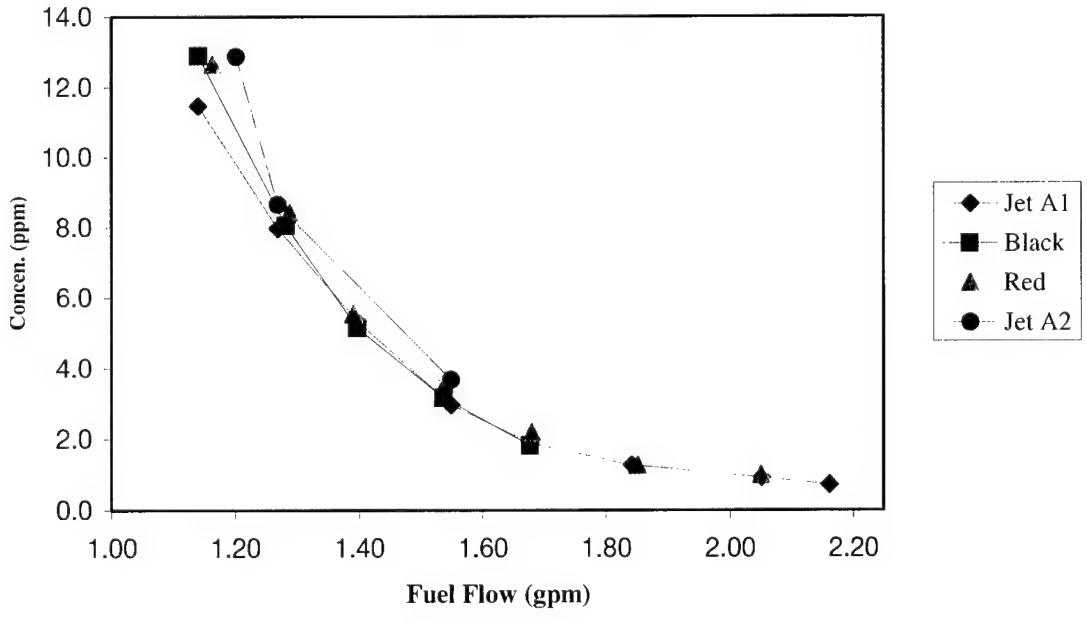


Figure 35: Concentration of Formaldehyde vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

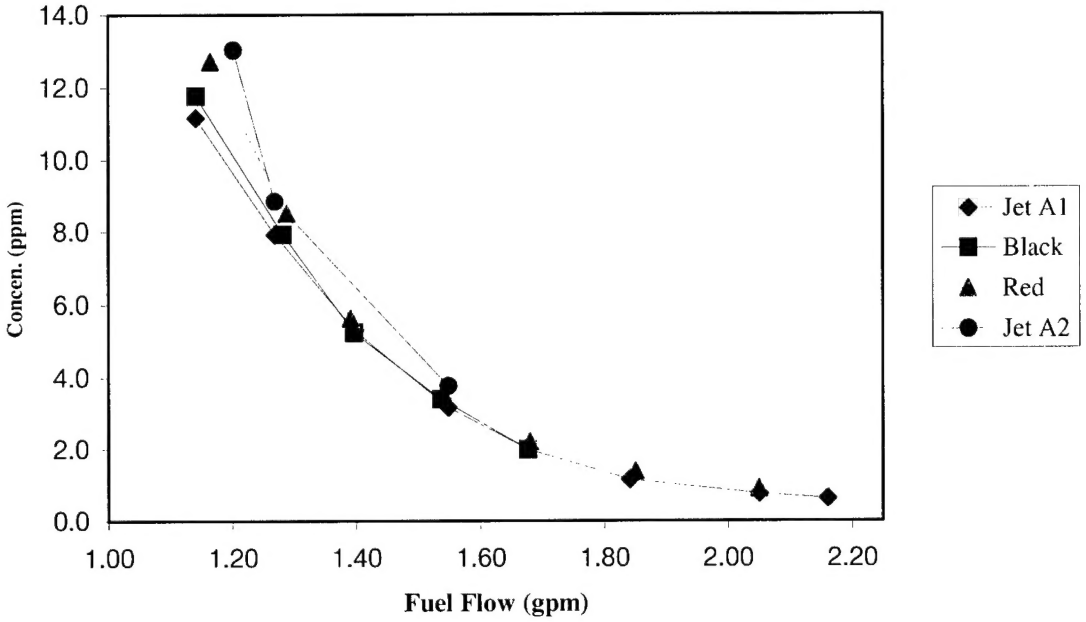


Figure 36: Concentration of Ethylene vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

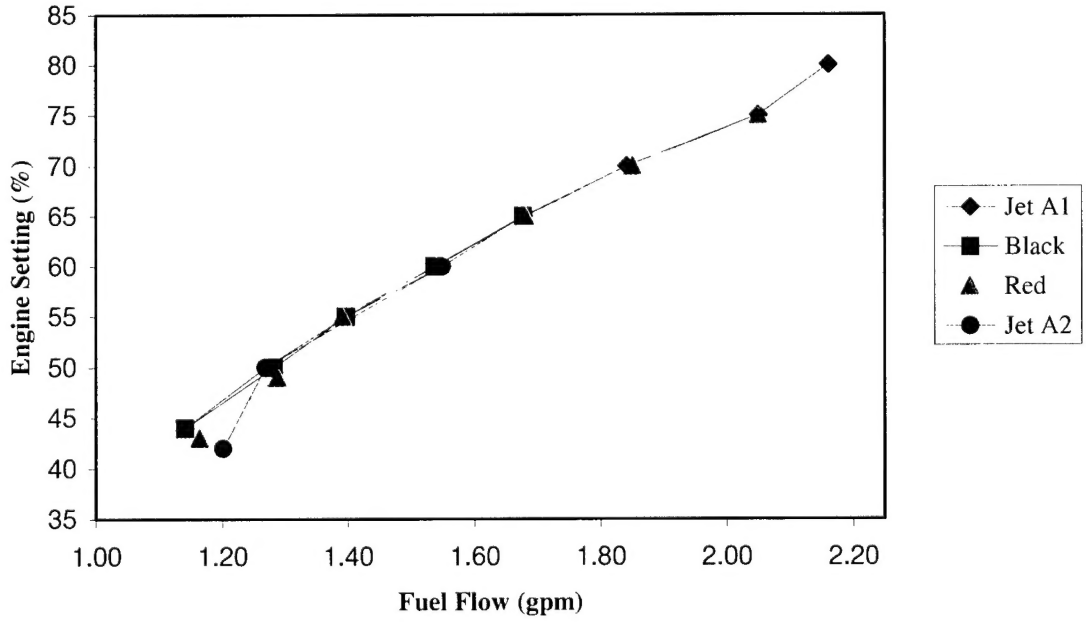


Figure 37: Engine Power Setting vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

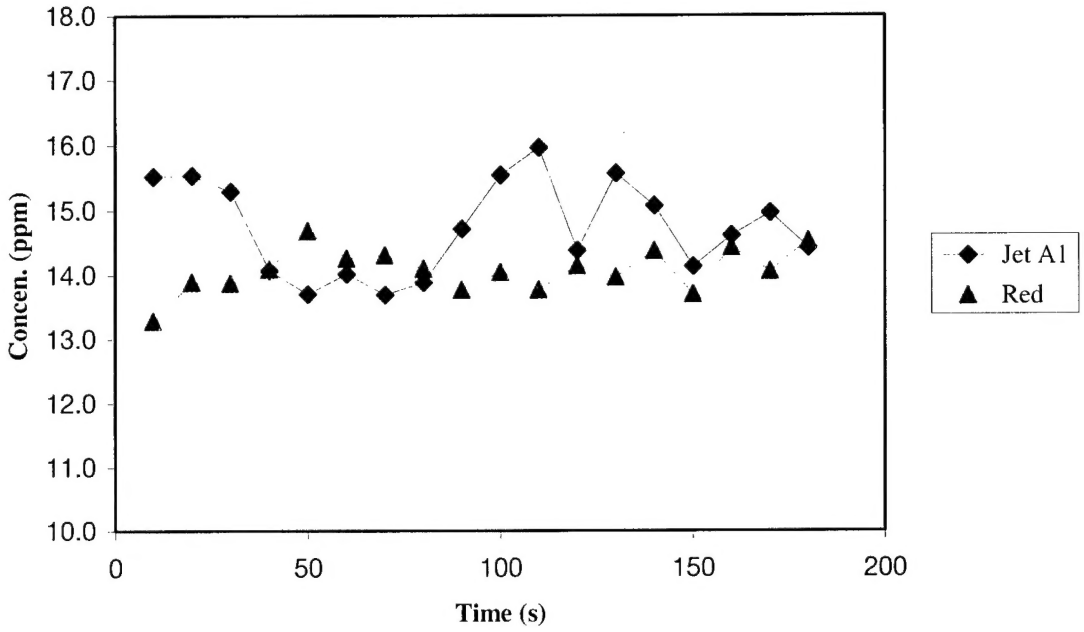


Figure 38: Concentration of NO_x vs. Time for Treated Jet-A from JT-12 Turbine Engine (Setting at 75%).

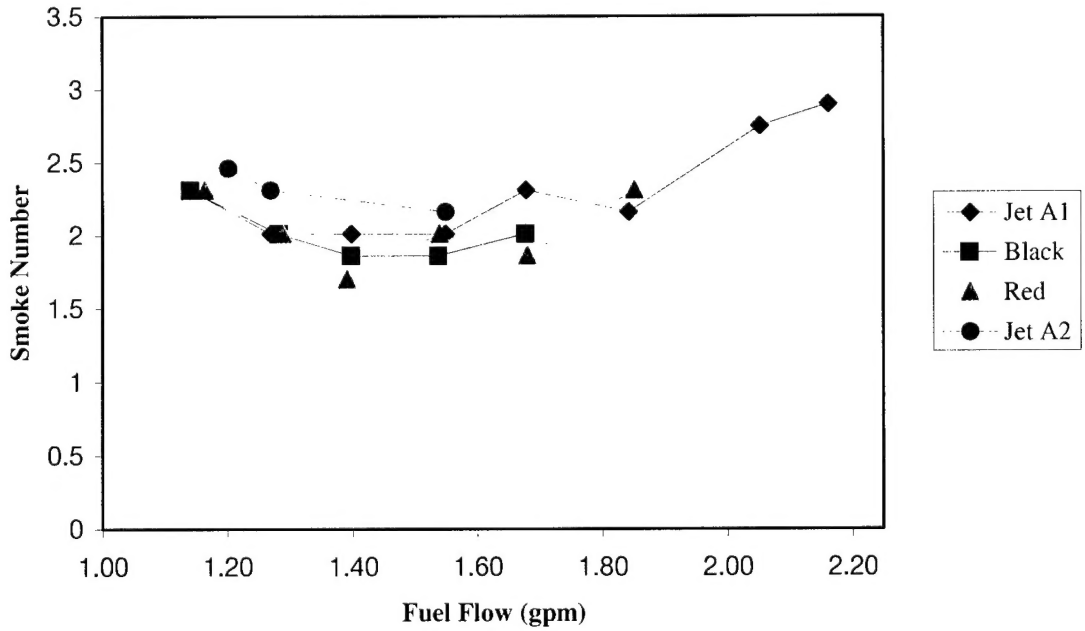


Figure 39: Smoke Number vs. Fuel Flow Rate for Treated Jet-A from JT-12 Turbine Engine.

Conclusion

During this Phase I effort, several catalyst formulations were tested for their potential for reduction in the exhaust emissions from an atmospheric modular combustor rig and a Pratt & Whitney JT-12 turbine engine. The Jet fuel was treated either by dropping small portions of catalyst (known as ingots) into the fuel storage container or allowing the fuel to pass through a catalyst filled canister that was installed directly into the fuel line for the combustor rig field test. The conditioning time (period of time the fuel was exposed to the catalyst) was approximately 90 hours for the "drop-in" ingots and estimated <1 minute for the "in-line" canisters. For the field test at MTSU using the JT-12 engine, Jet-A fuel was treated prior to testing for approximately 7 days (168 hours) with "drop-in" ingots of catalyst. On the day of testing the treated fuel also flowed through two "in-line" canisters for additional treatment. Neither field test showed any remarkable reduction in the exhaust emissions for any of the catalyst formulations tested.

Laboratory testing of two treated samples and one untreated sample of JP-8 jet fuel showed that the introduction of the catalyst did not degrade the mil-spec quality of the fuel for the set of mil-spec tests performed. The two treated sampled were conditioned for approximately 33 days (792 hours) before the laboratory tested the samples. All three samples were within mil-spec standards that are set for JP-8 fuel. Slight increases in particulate contaminants, between the three samples, were a result of the catalysts being in a raw cast form (i.e. not polished and cleaned before contact with the fuel). Yet, the particulate contaminants were still within mil-spec standards.

In Summary:

- APSI designed, and manufactured five different catalyst formulations for contact with jet fuel.
- Emission data was collected for untreated and for treated samples of jet fuel both on an atmospheric modular combustor rig (gas phase emissions monitoring) and a Pratt & Whitney JT-12 turbine engine (gas and particulate phase emissions monitoring).
- Analysis of the emission data showed no remarkable reduction in the exhaust emissions from the modular combustor rig or the JT-12 engine as a result of catalyst treatment.
- Laboratory analysis of the treated fuel showed that the catalyst did not degrade the mil-spec quality of the fuel, at least for the set of mil-spec tests performed.

Relevant to the chemical interaction of the APSI catalysts with jet fuels, APSI began three studies at the University of Connecticut in conjunction with Prof. Steven Suib's group in the chemistry department. These studies deal with the effects of the APSI catalysts on: 1) storage life of jet fuel due to auto-oxidation; 2) degradation of diesel and jet fuels due to the growth of microorganisms; and 3) molecular changes in diesel and jet fuels. A separate document reporting these studies was provided by APSI to the NAVAIR Technical Liaison/Point of Contact at the Phase I results presentation, held at Pratt & Whitney, East Hartford, CT, on 22 May 2002. Entitled "Fitch Fuel Catalysts Effects on Jet Fuel." These studies were funded independently of the Phase I project.

References

1. U. S. Patent No. 6,000,381: "Method and Apparatus for Treating Fuel," issued Dec. 14, 1999. Assignee: Advanced Power Systems International, Inc.

2. U. S. Patent No. 5,738,692: "Fuel Treatment Device," issued April 14, 1998. Assignee: Advanced Power Systems International, Inc.

3. U. S. Patent No. 5,625,118: "Method of Improving the Performance of Hydrocarbon Fuels," issued April 29, 1997. Assignee: Advanced Power Systems International, Inc.

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